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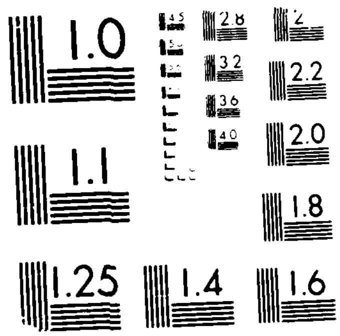

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DEPARTMENT OF OCEAN ENGINEERING

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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CRACKING TENDANCIES OF RESTRAINED WELDS IN HIGH STRENGTH LOW ALLOY STEELS UNDER HYPERBARIC CONDITIONS

by RANDOLPH NI

OCEAN ENGINEERING COURSE XIIIA
MECHANICAL ENGINEERING COURSE II

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(1)

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by

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B.S., Mathematics, U.S. NAVAL ACADEMY
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by

RANDOLPH NI

Submitted to the Department of Ocean Engineering on May 8, 1987 in partial fulfillment of the requirements for the Degrees of Naval Engineer and Master of Science in Mechanical Engineering

ABSTRACT

The weld cracking tendancies of two newly developed controlled rolled and accelerated cooled high strength low alloy (HSLA) steels are compared with a standard normalized steel of approximately the same ultimate tensile strength (50 kg/mm^2). All steels were welded with the shielded metal arc welding process at 0, 100, and 200 psig. Welding was conducted in a hyperbaric chamber under conditions of 100% humidity, using the Lehigh self restraint weld cracking test. A literature and mail survey was conducted on current U.S. practices in underwater welding using the shielded metal arc process.

Test plates were subjected to macroscopic examinations to determine the extent of any existent cracking. It was found that the low carbon equivalent HSLA steels exhibited an excellent resistance to cracking, even when welded without the use of preheat. The general tendency for cracking susceptibility to lower as the cracking susceptibility factor (P_w) lowers was validated, even under hyperbaric conditions. However, it was substantiated that the current theories used to determine cracking susceptibility may be too conservative in predicting cracking susceptibility for HSLA steels.

Thesis Supervisor: Dr. Koichi Masabuchi

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This thesis is dedicated to my parents Ernest In-Hsin Ni, Ph.D and Katherine Kao Ni, Ph.D. For my entire life, they stressed the value of education. Of all the people I know, I think that they would have been the proudest, and appreciated the culmination of my MIT education the most. I love you both dearly.

TABLE OF CONTENTS

		Page
Abstract		2
Acknowledgements		3
List of Figures		7
List of Tables		8
I.	Introduction	9
II.	Background	11
	2.1 Hydrogen Induced Cold Cracking	13
	2.2 Lehigh Weld Cracking Test	14
	2.3 HSLA Steels	18
	2.3.1 HSLA Manufacture	19
	2.3.2 Controlled Rolling	20
	2.3.3 Accelerated Cooling	22
	2.3.4 Development of HSLA Steel in U.S.	23
	2.3.5 HSLA Steel in the U.S. Navy	25
	2.3.6 Weldability	27
	2.3.7 Cost	28
	2.3.8 Comparison of U.S./Japanese Manufacture of HSLA Steels	29
	2.4 Steels being Evaluated	30
	2.5 Underwater Welding	31
III.	Hyperbaric Underwater Welding Using the Shielded Metal Arc Welding Process	35
	3.1 History and Overview	35
	3.2 Underwater Welding Techniques	38
	3.2.1 Inert Gas Shielded Methods	38
	3.2.1.1 GTA Welding	38
	3.2.1.2 GMA Welding	39
	3.2.2 SMA Welding	40
	3.2.3 FCA Welding	42
	3.3 Environmental Control of the Habitat	42

Table of Contents (cont.)

		Page
	3.4 Hyperbaric SMA Electrodes	46
	3.4.1 Weld Bead Geometry	46
	3.4.2 Electrode Diameter	47
	3.4.3 Consumable Covering	47
	3.5 Hydrogen Cracking of Underwater Welds	52
	3.5.1 Increased Hydrogen Absorbtion	52
	3.5.2 Prevention of Cold Cracking	55
	3.5.3 Pre- and Postheat	56
	3.5.4 Humidity Contribution to Hydrogen Absorbtion	57
	3.5.5 Prediction of Weldability	60
	3.6 Pressure Effects on Weld Metal Chemistry	61
	3.6.1 Increased Weld Impurities	61
	3.6.2 Gas Density Effects	64
	3.6.3 Welding Arc Effects	67
	3.7 Survey Results	69
IV.	Methodology	79
	4.1 Equipment Setup	79
	4.2 Parameter Selection	87
	4.2.1 Striking a Welding Arc	87
	4.2.2 Sensitivity Control	89
	4.2.3 Touch Retract Control	89
	4.2.4 Voltage Setting	90
	4.2.5 Amperage Control	90
	4.2.6 Start Adjust Setting	91
	4.2.7 Welding Speed	92
	4.2.8 Electrode Baking	92
	4.2.9 Preheat	92
	4.2.10 Final Settings	93
	4.3 Atmosphere	93
	4.4 Humidity	94
	4.5 Pressure Settings	96

Table of Contents (cont.)

		Page
	4.6 Selection of Welding Rods	97
	4.6.1 Initial Attempts	97
	4.6.2 Description of Weld Bead Irregularities	98
	4.6.3 Welding Rod Search	99
	4.6.4 Observations on Welding and Arc Stability	102
	4.7 Methodology Summary	104
	4.8 Data and Results	105
V.	Conclusions	110
VI.	Recomendations	113
Bibliography		115

LIST OF FIGURES

Figure	Title	Page
1-1	Repairs to Offshore Platforms vs. the Number of Installations in the North Sea	10
2-1	Lehigh Cracking Test Specimen	17
3-1	Maximum Arc Length vs. Pressure	37
3-2	Hydrogen Content in Weld Metal vs. Water Depth	43
3-3	Geometry of Weld Bead in Flat Position	48
3-4	Weld Metal Composition vs. Water Depth for Typical Low Hydrogen Electrodes	51
3-5	Moisture Absorbtion of Low Hydrogen Electrodes	51
3-6	Diffusible Hydrogen vs. Pressure	52
3-7	No Cracking Limit vs. Pressure	54
3-8	Hydrogen in Welds Deposited in Manned Simulator	60
3-9	Variation of Gas Content with Depth	62
3-10	Carbon and Oxygen Content in Weld Metal vs. Depth	65
3-11	Impact Properties vs. Depth	65
3-12	Sample Survey Cover Letter	71
3-13	Sample Survey Questionaire	72
4-1	Determination of Cracking Ratio	105

LIST OF TABLES

Table	Title	Page
2-1	Methods Available to Prevent Hydrogen Cold Cracking	15
2-2	Tested Steels - Alloying Elements and Property Summary	34
3-1	Water Absorbtion Under Hyperbaric Conditions	59
3-2	Variation of Gas Properties with Depth (typical)	66
4-1	Testing Parameters	107
4-2	Lehigh Cracking Results	109

I INTRODUCTION

The number of deep sea platforms, and consequently, the number of repairs to offshore structures has increased dramatically in the last two decades. Figure 1-1 shows the marked increase in the number of repairs and platforms from 1973 -1981 just in the North Sea.

These deep sea platforms and structures are in many cases constructed of high strength steels. Consequently, when welding repairs must be conducted on these structures, engineers must deal with the problems of high strength steel's sensitivity to hydrogen cracking.

When welding at deep depth, the problem of hydrogen cracking is accentuated over normal atmospheric welding due to the possibilities for increased hydrogen absorbtion from the underwater welding conditions.

It is apparent that to facilitate construction and repair of these offshore structures that it is increasingly imnportant to develop and utilize high strength steels that are resistant to hydrogen cracking. High strength low alloy (HSLA) steels are already known for their resistance to hydrogen cracking.

It is the purpose of this thesis to examine the weld cracking resistance of three types of steels when welded under hyperbaric conditions. The Lehigh cracking test was used to study the weldability of these steels at three pressures (0, 100, 200 psig) utilizing the shielded metal arc

(SMA) welding process. In pursuit of this goal a literature and mail survey was conducted to gain an appreciation of the state of the art of underwater hyperbaric welding using the SMA welding process.

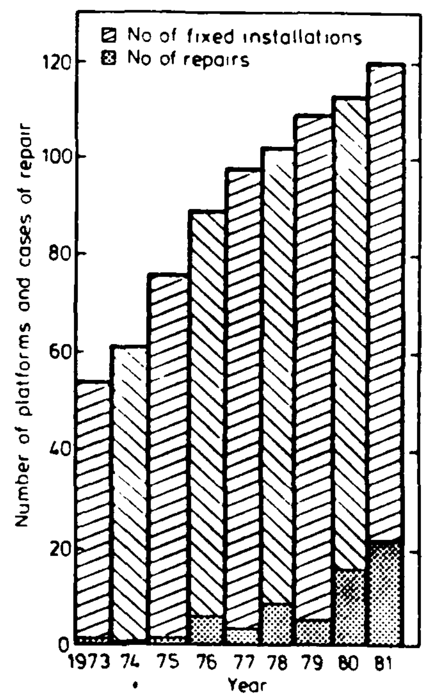


Figure 1-1 Repairs to Offshore Platforms vs the Number of Installations in the North Sea (Reference 14)

II BACKGROUND

This is the third thesis related to a research program sponsored by the Iron and Steel Production Division of KOBE Steel, Ltd. The title of the research program is "Research on High Strength Steels with an Improved Resistance Against Weld Cracking".

The objectives of this research program for KOBE Steel are (1) to evaluate resistances against weld cracking of a few selected types of high strength steels developed by Kobe Steel, and (2) to study how the availability of these new steels can affect welding procedures used for fabricating welded structures, especially large marine structures, and their fabrication costs.

The high strength steels developed by Kobe Steel have excellent resistance against weld cracking. They include controlled rolled structural steels and quench and tempered structural steels. Both type steels are characterized by (1) markedly reduced carbon content, (2) relatively high amounts of alloying elements, and (3) applications of precisely controlled rolling and heat treatments. They are both in the classification of high strength low alloy (HSLA) steels.

The previous individuals and their theses who carried out earlier portions of this research study were:

F.F. Hillenbrand, III, "Research on High-Strength Steels with an Improved Resistance Against Cracking", M.S. Thesis, June 1984.

M.J. Purcell, "Hydrogen-Induced Cracking in Three High Strength Steels", M.S. Thesis, August 1984.

Cracking tests were performed using three types of tests including the Tekken test, the Lehigh test, and the MIT test. As anticipated, it was found that the Kobe Steel K-TEN80CF had significantly superior resistances against cracking compared with HY-80 steel and T-1 steel Type A.

This thesis will endeavor to commence work that will contribute to the determination of carbon equivalent values for steels that can be safely welded underwater in dry hyperbaric conditions. The objective of this portion of the Kobe study is to investigate the suitability of the new type steels for underwater welding, which is an important requirement for steels to be used for offshore structures.

Underwater welding techniques may be classified as 'wet' and 'dry' welding depending upon the environment in which welding operations take place. Welds that require good metallurgical and mechanical properties are normally made under dry conditions. Dry hyperbaric welding techniques, in which the pressure of the dry welding environment increases as the water depth increases, are widely used for obtaining high-quality welds for repair and some new construction. However, despite the term 'dry' welding, the welding environment is still very humid, thus providing a source of hydrogen to enter the weld pool and promote hydrogen cold cracking. Therefore, there is an extreme advantage of using these new steels, if it is proved that these new steels have superior resistances against weld cracking than conventional steels with comparable strength levels, when welded under humid environments at various pressures. Then, one could say that these new steels would be essential for fabricating offshore structures.

This thesis will accomplish two goals. First, it will summarize the state of the art of hyperbaric welding using SMA welding. Secondly, it will perform experiments to help determine the cracking susceptibility of varying grades of carbon equivalent steels when welded under hyperbaric conditions.

It is not the intent of this thesis to rehash background information already covered in Purcell's or Hillenbrand's theses (References 25 and 26). Coverage of the subjects of hydrogen cracking and weld cracking tests will be brief. The reader is invited to review either the original sources or the previous theses related to this research program for more detailed information on these topics

2.1 Hydrogen Induced Cold Cracking

High strength steels are noted for their susceptibility to hydrogen induced cold cracking. It is usually assumed that this phenomena is associated with the hydrogen embrittlement of martensite or bainite and that it is initiated by high residual stresses developed in the weld joint during cooling. The factors responsible for the problem have been summarized in detail in the literature (References 25 and 26). Conditions that cause hydrogen cracking are tensile stress on the metal, temperature from 100 to 200 degrees C, a source of hydrogen, and a susceptible microstructure.

Four general classifications of theories regarding hydrogen cracking exist and are listed below:

Planar pressure theories

Surface adsorbtion theories

Triaxial stress theories

Dislocation theories

Prevention of hydrogen induced cold cracking involves removing or minimizing one or more of the conditions that cause the problem. A brief listing of the methods available is provided in Table 2-1.

2.2 Lehigh Weld Cracking Test

The Lehigh weld cracking test was selected to be used for this thesis. Its selection was predicated on the ease of use, familiarity with the test , and the fact that the preceeding theses related to the encompassing research project (References 25 and 26) on the cracking tolerances of

TABLE 2-1

Methods Available to Prevent Hydrogen Cold Cracking

Minimizing Hydrogen in the Weld

Minimize humidity in the air

Minimize moisture in the electrode

Keep welding surface and consumable clean of dirt, hydrogen compounds (grease, degreasing fluids,oil), coatings (oxides, paint), or moisture

Use low hydrogen electrodes

Use an inert gas environment

Preheat, Postheat

Use low hydrogen welding process.

Relieving Stress Through Proper Design and Fabrication Procedures

Postheat

Minimize thermal stresses (Preheat)

Proper weld joint geometry and selection

Controlled low temperature stress relief

Vibratory stress relief

Peening

Prevention of a Susceptible Microstructure

Utilize fine grained steels

Control cooldown rate by adequate preheat or interpass heating to minimize grain growth

HSLA steels had used this test. The other obvious candidate tests to be used were the MIT test and the Tekken test, which were also used by Hillenbrand and Purcell. Although samples were prepared of the Tekken test, time limitations prevented conducting any welding at hyperbaric pressures. Further tests are scheduled to be conducted by other individuals.

The Lehigh weld cracking test has been a popular self restraining test used in the US since its development at Lehigh University in the 1940's. It has been previously used to rank steels and electrodes and develop adequate welding procedures. Figure 2-1 shows the standard Lehigh test plate specimen used in this research. A detailed description of the Lehigh test and specimen preparation are provided in References 1, 25 and 26. The restraint of the weld may be varied with saw cuts on both the edges and the ends of the plate. This option was not selected as it was desired to achieve the maximum restraint attainable with the Lehigh test. Even with no sawcuts, the level of restraint achieved with the Lehigh test is considerably less than with other tests, i.e. the Tekken test, and may be less than in actual structures, should there be any sawcuts.

Weld cracking was evaluated with single pass welds. This simplified the testing process and experience has indicated that the root is the most likely location for cracking. Root cracking is enhanced because the preheat temperature is typically at the specified minimum, the energy

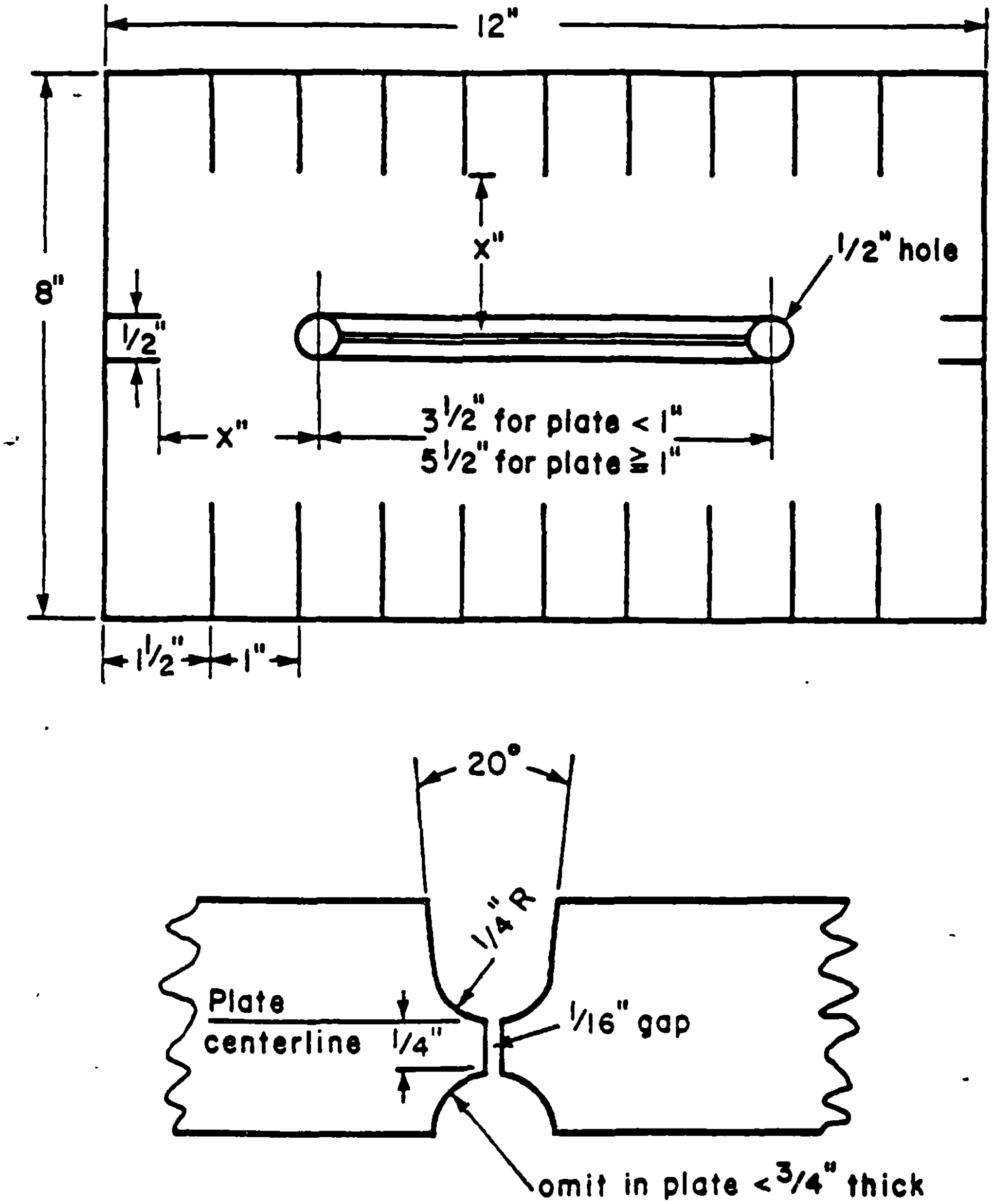


Figure 2-1 Lehigh Cracking Test Specimen
(Reference 1)

input is often lower than the subsequent passes, and high restraint and stress concentrations usually exist.

Determination of whether weld cracking had occurred was accomplished by sectioning, polishing, and macroscopic examination generally after 60 to 72 hours. Welds were sectioned in three equally spaced locations.

A disadvantage of the Lehigh test is that it is a "go" "no-go" test. In other words, if the test sample does not crack, very little is learned. However, if the test plate does crack, all that is learned is that less restraint is required for the plate not to crack.

2.3 HSLA Steels

The new types of HSLA steels were developed to satisfy the requirements of the offshore structure and pipeline industries for a low temperature high strength, high toughness steel that could be fabricated in adverse conditions, i.e., easily weldable. This requirement, in the 1960's and early 1970's, prompted improvements in the steelmaking industry for production of 'clean steels', and later easily weldable high strength ferritic steels now called HSLA steels. Essentially, these were new types of C-Mn steels of bainite, acicular ferrite and reduced pearlite microstructures.

HSLA steels are ferritic and/or pearlitic with fine grain size and carbon levels below 0.15%. HSLA steels have potentially the same or better strength and toughness properties as other high strength steels, e.g., the HY series, but HSLA properties are obtained by a combination of 'clean' steel processing, carefully selected small amounts of micro-alloying elements, and heat treatments resulting in a ferritic more easily welded microstructure. The micro-alloying of HSLA steels consists of additions of small amounts (less than 0.15 weight percent) of elements such as Cb, V, Ti, Al, B, and N which function in grain refinement and precipitation hardening to increase strength and toughness in a conventional C-Mn structural grade steel. Further increases are achieved with nominal amounts of conventional alloying of Cu, Co, Ni, and Mo along with refinement of microstructure transformation products and grain size during rolling, as well as optimization of the type and distribution of the strengthening precipitates. The results are steels which, because of low carbon content, are extremely weldable without the use of many of the stringent process controls required for other high strength steels. (Note: it has been demonstrated that when a steel has less than 0.10% C, good weldability is more easily achieved even with significant other alloying. (Reference 4))

2.3.1 HSLA Manufacture

The new approaches to steel making have several common features which emphasize microalloying and thermomechanical processing. A key element of the HSLA technology is the very fine grain size. Grain refinement is unique of all the strengthening mechanisms (carbon equivalent, precipitation hardening, solid solution hardening, work hardening, etc.) in that it is the only mechanism which simultaneously increases the strength and lowers the Charpy transition temperature. The grain size is reduced through the addition of microalloying elements, by a decrease in the rolling temperature and an increase in reduction, and by the lowering of the ferrite transformation temperature by either increasing the cooling rate and/or increasing the hardenability of the steel. (Reference 20)

HSLA steels are not only used in applications of heavy plate products, but in sheet metal and lighter gauge applications (i.e., the automobile industry), however, all types of HSLA steels utilize the same features of grain refinement to increase the strength and fracture toughness properties.

2.3.2 Controlled Rolling

Prior to the advancement of HSLA steel technology, the normal means to achieve a fine grained microstructure was to utilize conventional controlled hot rolling.

The purpose of modern controlled rolling is to obtain a uniform, fine grained structure in the hot-rolled condition and thereby to produce steel with high strength, good toughness at low temperatures, and superior weldability. In order to attain this purpose, chemistry, slab-reheating temperature, hot-rolling, transformation behavior, and cooling rate must be properly controlled. Conventional controlled rolling involves the control of hot-rolling conditions alone. (Reference 17) This is as opposed to the modern controlled rolling process, which covers the whole process from slab-reheating and hot-rolling to controlled cooling. Modern controlled rolling can produce not only a fine-grained ferrite structure, but acicular ferrite and dual-phase structures.

The fundamental difference between conventionally hot rolled steel and modern controlled rolled steel lies in that, in the former, ferrite grains nucleate exclusivly at austenite-grain boundaries, whereas in the latter, nucleation occurs in the grain interiors as well as grain boundaries, that ferrite-nucleation frequency is larger at deformed austenite grain boundaries than at recrystallized ones, and that isolated ferrite nucleation occurs in the interiors of deformed austenite grains. These effects lead to a large difference in the final ferrite grain structure in the two steels. (Reference 17).

In summary, modern controlled rolling is used to produce fine ferrite grains and thereby to increase the yield strength and to lower the transition temperature.

2.3.3 Accelerated Cooling

Other strengthening mechanisms following the controlled rolling process can be quenching and tempering, precipitation hardening, or quenching and age hardening. It is sometimes not even necessary to do a post controlled rolled heat treatment if the controlled rolling is done at finishing temperatures below the austenitic decomposition temperature (approx. 700 degees C.) (Reference 23) This process is used in the manufacture of ultra low carbon bainitic steel or in ferritic- pearlite steel. The drawback to this process is that it is not possible to accomplish without extremely powerful finishing stands not currently available in the US.

A recently developed process, only first incorporated into a manufacturing process in 1979, is the strengthening process of accelerated cooling. In this process, increase in tensile strength is brought about by the fine dispersion of hard second phase particles. The result is an even finer grain size than that achievable through controlled rolling alone at high finishing temperature, and an equally fine grain structure as that achieved by low temperature controlled rolling processes. Contrasted to controlled rolling, in which beneficial effect is obtained primarily by grain refinement through the control of the austenitic microstructure, accelerated cooling can stengthen the steel while maintaining superior toughness by transformation strengthening through the control of the gamma to alpha transformation. (Reference 18) Further, by appropriately varying the process parameters, different combinations of microstructure and hence mechanical properties can be attained with the same chemical composition of the steel. (Reference 22). Accelerated cooling has the distinct advantage over quenching in that it does not involve a post cooling tempering treatment, and thus, it is applicable to a variety of as-rolled plate. For direct quenching, a tempering treatment cannot be eliminated, and its application is restricted to heat treated steels. It is also much cheaper than the quench and temper process, and produces a product with better mechanical properties. Accelerated cooling, as yet, has not been introduced to the US as an on line manufacturing process.

There are even more variations on the means to manufacture HSLA steels. This paper will not elaborate on them as those processes produce steels that are not presently in consideration for application to construction of offshore platforms.

2.3.4 Development of HSLA Steel in the US

The history of HSLA steel in the US goes back to the turn of the century when the Queensboro Bridge was being built across New York City's East River. The Carnegie Steel Company provided the solution to the bridge builder's desire to minimize structural dimensions by manufacturing the first

HSLA steel (containing 3.25 % nickel). Development continued, and it was learned that small additions of silicon and manganese would also increase strength. In 1933, US Steel manufactured a 50 ksi yield strength weathering steel which had attributes of high strength, high ductility, good formability, good weldability and high corrosion resistance. These properties were achieved through the addition of alloying elements of C, Mg, Si, Cu, P, Ni, and Cr. At this time, it was also discovered that Cu additives would also provide a favorable precipitation hardening effect, but this fact could not be capitalized on for manufacturing purposes due to the lack of knowledge of how to effect it on a large scale. It was subsequently learned that yield strength could be further enhanced by addition of a small amount of Niobium or Vanadium (micro-alloying), and controlled rolling (rolling at lower than normal temperatures). This process caused suppression of the austenitic grain growth and resulted in a smaller grain size.

In 1967, pressured by industrial demand to develop a high strength, high toughness, weldable and economic steel, International Nickel Corporation developed the first steel to take advantage of Copper as a precipitation hardening agent. They developed NICUAGE, which was an age hardenable Nickel, Copper, Niobium steel with a -15degree F. DBTT. Development of the arctic pipeline prompted further refinement of NICUAGE by addition of Chromium and Molybdenum with prescribed heat treatments to even further lower the DBTT to -115 degrees F. This steel was called IN-787. The strength and toughness level of IN-787 prompted research into its compatibility to ship construction and maritime applications. A three year testing program resulted in the finding that it could be used with confidence by the shipbuilding and offshore industries, and resulted in the maritime application steel designation ASTM-710.

2.3.5 <u>HSLA Steel in the US Navy</u>

An example of a modern HSLA steel is the type steel currently used be the U.S. Navy, which is an acicular ferrite steel. These steels have low carbon levels, can generate yield strengths over 80 ksi and have a very low DBTT of less than -100 degrees F. The type steel selected by the Navy is ASTM A710. This steel was developed by the International Nickel Company and when manufactured to government specifications is called HSLA-80. The steel has low carbon (0.04 - 0.08) for good weldability and uses C, Mn, Ni, Cr, Mo, Cu, Cb, and Al as alloying elements, their purposes for use which are listed below:

manganese - ties up sulpher
reduces hi temp transformation products
provides solid solution strengthening

copper - precipitation strengthening

chromium - optimize precipitaion of Cu

molybdenum - optimize precipitaion of Cu

nickel - prevent hot shortness from Cu

increase toughness

aluminum - deoxidizing, grain refining

columbium - retard austenite grain growth

(Reference 4)

After quenching, the structure consists of a mixture of very fine-grained ferrite, acicular ferrite and a martensite-austenite microconstituent, together with a high dislocation density. Aging produces an even finer dispersion of epsilon-Cu precipitates. The fine scale microstructure is the key factor producing the good combination of strength and toughness. (Reference 19)

The key advantage of HSLA steels in naval ship construction is their inherent weldability and attendent lack of pre-heat requirement as part of the welding process. Substitution of HSLA for HY-80/100 can yield cost savings mot only through lower fabrication costs but through lower material costs as well. Weight savings can additionally be achieved by substitution of HSLA steels for lower strength high strength steels (HTS), since smaller cross sections can be specified. Further, the weight savings can be achieved with only an increase in the cost of the steel plate itself, since fabrication of HSLA and HTS steels are accomplished by essentially the same process. (Reference 4)

2.3.6 Weldability

Weldability represents a good deal of the cost savings to be expected with HSLA use. Traditional high strength steels are very susceptible to hydrogen cracking in the heat affected zone (HAZ) from welding. In order to eliminate the hydrogen damage during welding, the plate must be preheated before welding. This is a very costly and labor intensive procedure, and is a main cost driver in fabrication and repair. HSLA steels have virtually eliminated preheat requirements before welding. (Reference 24)

Some of the most significant factors being investigated with regard to the welding of fine-grained low-alloy steels for construction purposes are the requirements for low welding energy input and limitation of interrun temperatures so as to achieve welded joints with good mechanical properties in the weld metal and HAZ. Low welding heat input has been shown to be necessary to minimize the formation of coarse grain structure in the HAZ and to avoid secondary carbide precepitation. These defects can increase the susceptibility of the HAZ to crack. However, the low welding energy requirement means a reduced weld bead cross section per run, and hence substantially more weld runs are required to fill a given joint volume. (Reference 21)

Weldability studies indicated that weld metal and HAZ properties were acceptable with current welding procedures and practices (i.e., cooling rates kept above 10 degrees F.)

The elimination of preheat as a requirement was validated, and it was further determined that HSLA was less susceptible to hot cracking than HY series steels. Large scale production weldability tests demonstrated that cracking only occurred when the HSLA was welded in extreme conditions (i.e., outside specified welding parameters). (Reference 4)

It is noted that some HSLA steels have been specifically developed to retain significant toughness levels in the HAZ, even when welded with high heat input, high deposition rate processes. These type steels have been specifically validated as appropriate for maritime use by a research project sponsored by the American Bureau of Shipping, the Society of Naval Architects and Marine Engineers, The US Maritime Administration, and others. These type steels were all manufactured with either Thermomechanical Controlled Processing or Thermomechanical Controlled Rolling (both, processes not available in the US), and possess extremely low sulfer levels, low carbon equivalent levels, fine ferrite grain size, and intentionally added titanium.

2.3.7 Cost

The net cost differential of HSLA steel over a typical high strength steel such as HY-80 has been estimated to be $0.40 to $0.90 per pound of steel; or 5% to 15% less cost than for HY-80/100 (Reference 24). It is important to note that this does not include an estimate for other HSLA steel advantages beyond material cost and preheat, which are related to the capability to easily weld the materials. These include lessened non-destructive testing, the ability to weld through paint primer, reduced requirement to NDT the back-gouging of root passes, and no necessity to grind off temporary attachments instead of flush removal as are required for HY-80. (Reference 4)

2.3.8 Comparison of US/Japanese Manufacture of HSLA Steels

The US currently lags well behind the Japanese in the manufacture of HSLA streels. Currently the Japanese make stronger, cleaner steel than the US is capable of making. Their clean steel technology is better than the US, as evidenced in their more extensive and superior ladle treatment. The reduction of sulfer, phosphorus, nitrogen and oxygen in a steel improves the toughness in both the base metal and HAZ. The sulfide or phosphide formed in a steel can dissolve and precipitate in the HAZ lowering toughness. Thus, Japanese steels are achieving better toughness, with less additives, making their steel a more weldable steel. TMCP, using accelerated cooling, and TMCR, a post hot controlled rolling procedure in the austenitic-ferrite two phase region, have not been introduced into any US steel mill. Thus, the US is not able to manufacture many of the types of HSLA steels that are possible with current world technology.

The poor state of US steel making technology is reflected in its research capability. As an example, Bethlehem Steel sold its research facilities to Lehigh University - and now rents back a small portion of the space. Another company, which had a research staff of 1300 plus employees now has only around 200. Some Japanese companies now have over 1600 employees in their research departments.

An example of the problems this presents for the U.S. is that the Navy wants to buy US steel, but no US Steel manufacturer can provide the quality steel the Japanese make. It is not cost effective for US steel manufacturers to upgrade a steel mill capable of making 6-9 million tons per year of steel just for the US Navy, which might buy only one-half million tons per year, if they should get the contract. The US manufactures a lot of HSLA steel, but most of it is sheet steel for the automotive industry. The unquestionable leader in plate steel remains the Japanese.

2.4 Steels Being Evaluated

Three type steels were evaluated for their hyperbaric welding performance. All steels had ultimate tensile strengths around 50 kgf/mm^2 (71 ksi) and yield strengths around 40 kgf/mm^2 (57 ksi). The Type I steel is a conventional type steel whose properties were obtained through normalization. Its PCM was the highest at 0.228 (C.E. = 0.373). Both Type II and Type III steels are HSLA steels whose properties were obtained from controlled rolling and accelerated cooling. The Type II steel had a PCM of 0.193 (C.E. = 0.315). The Type III Steel had a PCM of 0.154 (C.E. = 0.292). Table 2-2 provides a summary of principle alloying elements and properties.

2.5 Underwater Welding

The advances in technology involving underwater welding have been generated from the increasing number of underwater platforms existing in the world. These underwater platforms will eventually require repairs, and the scope of the repairs will eventually require underwater welding. A number of welding processes have been used and studied for underwater applications. The most commonly used are the arc welding processes including the shielded metal arc (SMA) process using covered electrodes, the gas metal arc (GMA) process, the gas tungsten arc (GTA) process, and the flux cored arc (FCA) process. Other welding processes that have been used and/or studied include submerged arc, plasma arc, stud, thermit, friction, resistance welding, etc. (Reference 12).

The American Welding Society (AWS) has classified the underwater welding techniques on the basis of the environment in which the welding takes place, as follows:

A. Dry Chamber Techniques. Welding takes place in a dry environment.

1. One-Atmosphere welding. Welding is performed in a pressure vessel in which the pressure is reduced to approximately one atmosphere independent of depth.
2. Hyperbaric Dry Habitat Welding. Welding is performed at ambient pressure in a large chamber from which water has been displaced by a gas to provide a dry environment. The welder/diver does not work in diving equipment.
3. Hyperbaric Dry Mini-Habitat Welding. Welding is performed in a simple open-bottom dry chamber which accommodates the head and shoulders of the welder/diver in full diving equipment.

B.. Portable Dry Spot Technique. Only a small area is evacuated and welding takes place in the dry spot.

C. Wet Technique. Welding is performed in water with no special device creating a dry spot for welding. In manual wet welding the welder/diver is normally in the water.

(Reference 7)

By far the most popular underwater welding classifications used have been the wet technique and the hyperbaric dry habitat welding.

Major advantages of wet welding are its simplicity and its ability to be used in the wet environment. The major shortcoming is the rather poor weld quality compared to that of welds made in air (Reference 12) due to the intensive cooling of the welds, resulting in the formation of quenching structures, and the high content of diffusion-mobile hydrogen in the weld metal. All factors which promote the occurence of cold underbead cracks, the decrease of toughness and impact resistance in the metal. Underwater wet welding processes are widely used for repair jobs because of this process' significant cost saving over other underwater welding methods which yield higher quality welds.

Since hyperbaric dry habitat welding is done in the completely dry environment, the quality of these welds can match the quality of welds made in normal atmospheres and pressures. This type process is used for critical jobs where structural integrity and fatigue considerations are paramount. The major problem of this process is the extremely high cost.

This thesis only addresses that facet of underwater welding concerned with the use of SMA welding in a hyperbaric dry environment.

TABLE 2-2

TESTED STEELS
ALLOYING ELEMENTS AND PROPERTY SUMMARY

	TYPE I	TYPE II	TYPE III
UTS (kgf/mm^2)	54	51	53
Y.P. (kgf/mm^2)	39	38	34
Elong. (%)	29	29	28
C (%)	0.15	0.13	0.08
S (%)	0.33	0.21	0.35
Mn (%)	1.34	1.11	1.11
P (%)	0.013	0.015	0.008
S (%)	0.007	0.009	0.001
Al(%)	0.024	0.033	0.031
Ni (%)	----	----	0.40
Nb (%)	0.031	----	0.011
Ti (%)	----	----	0.007
Ceq (%)	0.373	0.315	0.292
Pcm (%)	0.228	0.193	0.154

$$Ceq(\%) = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$$

$$Pcm(\%) = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$$

III HYPERBARIC UNDERWATER WELDING USING THE SMA WELDING PROCESS

3.1 History and Overview

The concept of underwater dry habitat welding on pipelines essentially began with the 1954 patent by Osborn. He developed a design of an underwater enclosure that was to become the predecessor of contemporary welding habitats. The concept was too futuristic for its time, however, and did not receive much attention until shortly before it expired, with the large advent of underwater structures and pipelines. Commencing around 1965, several companies involved in diving and related activities built various types of underwater welding habitats and performed repairs on offshore platforms and pipelines. *The techniques originally developed for* pipeline tie-in and repair have since been adapted to riser tie-ins on concrete platforms, repair of damaged offshore structures, and many other applications. (Reference 7) Underwater dry habitat welding is conducted on a routine basis at depths in excess of 150 m (500 ft) and have been accomplished at sea depths of 320 m. (Reference 8) Most of the work thus far has been done in the Gulf of Mexico and the North Sea.

The control of welding parameters, gas shielding and selection of consumables all become more critical with increased operational working depth. In the view of one welding contractor (Reference 15), SMA welding reaches its working limit at around 300 m, due to the increased susceptibility to hydrogen cracking. This particular contractor endorses GMA welding for deeper depths.

One of the primary effects of welding under pressure is the constriction of the arc and the volumetric shield surrounding the arc, this results in a decrease in arc stability. Due to the reduced arc stability, smaller diameter welding consumables, typically 2.5 and 3.2 mm electrodes, are used for positional welding when using the SMA welding process.

Additionally, the fusion characteristics of SMA welding deteriorate with pressure, it is therefore necessary to ensure that short arc lengths are maintained in order to achieve the required weld properties. Figure 3-1 relates how the maximum arc length shortens with pressure.

Weld metal chemistry also changes with pressure in SMA welding. Gases from the environment are absorbed at greater rates than in normal atmospheric welding which can affect impact values and crack susceptibility, including hydrogen cold cracking. Thus, preheat temperatures are higher, and welding consumable hydrogen/moisture control is more stringent than for conventional atmospheric welding. Additionally, post weld hydrogen diffusion treatments have sometimes been specified to reduce the level of hydrogen retained in the welded joints, typically at temperatures of 200 to 254 degrees C.

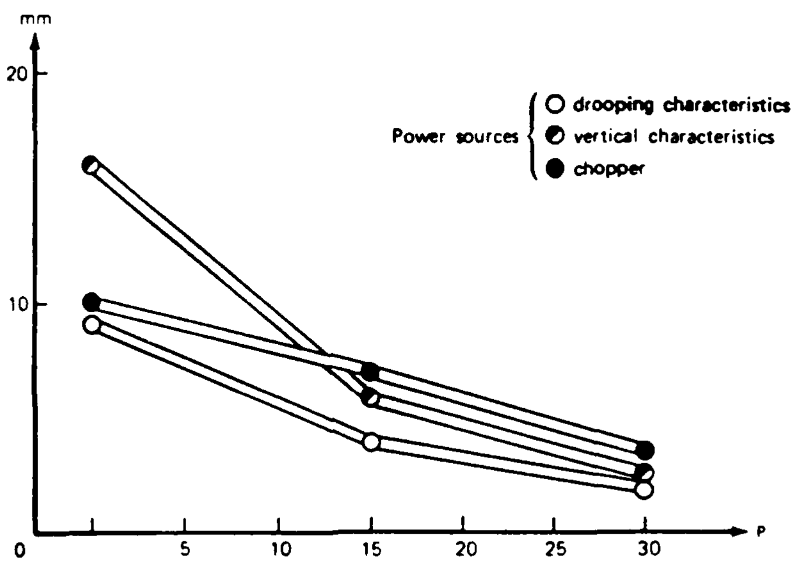


Figure 3-1 Maximum Arc Length vs. Pressure
(Reference 13)

3.2 Underwater Welding Techniques

High quality connections which satisfy the most stringent specifications can be made by current welding techniques. The optimum welding technique or combination thereof appears to be a function of individual welding contractor preference, proficiency or expertise. A combination of using GTA welding for the root and hot pass followed by SMA welding for the fill and cap passes seems to be the most popular consensus of preferred welding sequences. However, the advantage of only using SMA welding or only using GMA welding has been espoused in the literature.

3.2.1 Inert Gas Shielded Methods

The inert-gas shielded processes are able to produce welds of a much lower impurity content. Carbon will in general not be introduced into the weld, and although hydrogen may be picked up from the humid habitat atmosphere, hydrogen absorbtion will be overall much smaller, an average of about 5 ppm in the weld metal from welds made at 500 ft (16 bar) being virtually independent of the habitat humidity. (Reference 8)

3.2.1.1 GTA Welding

GTA welding was initially used for the entire weld by one welding contractor, as it met the requirements for producing a root bead of a convex contour with satisfactory metallurgical and mechanical properties. (Reference 7)

However, due to it being a very slow process, its use is currently confined to welding the root and hot passes. The disadvantage GTA welding posed to another welding contractor, which does not use GTA welding, is related to this particular contractor's desire to work in "shirt-sleeve" conditions without breathing masks. GTA welding was eliminated since argon has a narcotic effect and connot be effectively removed by the gas regeneration system. In addition, GTA welding was considered too slow and subject to magnetic arc blow, possibly requiring demagnetization of the components to be welded. GTA welding in helium was found too difficult to perform. This welding contractor's extensive development and research has concentrated on SMA welding, GMA welding and FCA welding. (Reference 11)

3.2.1.2 GMA Welding

People who endorse GMA welding provide the following attributes of this technique over that of SMA welding. The absense of an external coating and reduced moisture absorption means that for certain materials, welding can be done without preheating. The alignment and joint tolerances are greater. The process is capable of higher deposition rates with no down-time for electrode changing. Better mechanical results than the SMA welding were achieved with respect to ductility bending, elongation and toughness. GMA welding is not affected chemically by pressure. Welder training is simplified. Penetration is easier, visibility and handleability of the arc are improved. Sensitivity to hydrogen cracking is considerably reduced. As opposed to the SMA welding process, which was felt to be intrinsically limited in depth to approximately 300 m, the GMA process has no depth limit. (Reference 15)

People who do not endorse the GMA process cite these disadvantages of the process. Although the welding speed of the GMA process is high, it tends to produce a concave-shaped root pass; also, lack of fusion possibilities and wire feed problems tended to offset the gain in deposit rate. (Reference 7)

3.2.2 SMA Welding

The SMA welding process using low hydrogen type electrodes is currently the most widely used underwater welding process. Good penetration with a reasonable welding speed can be achieved under hyperbaric conditions. (Reference 7) By modification of the coating, using a short arc technique, and increasing the arc voltage, stable arc welding conditions can be achieved at pressure. (Reference 11) Although the electric arc characteristics are affected a little by pressure, they are generally excellent. It is important to prepare the electrodes very carefully and transfer them perfectly dry. Using dry electrodes and the highest energy input possible are two key factors in minimizing hydrogen cracking. String beading procedures which are used produce good toughness qualities but is unfavorable as far as hydrogen cracking and hardness in the HAZ are concerned. Less hardenable metals are recommended for hyperbaric welding with carbon equivalents less than 0.40 if possible. (Reference 15) Welding machines should have excellent dynamic characteristics and a device for restriking the arc. (Reference 11)

The effect of pressure does lead to increased absorbtion of hydrogen (on the order of 2.5 times the content in surface welds), oxygen and carbon and to reduced contents of silicon and manganese. Utilization of inert gas atmospheres minimizes the problems associated with impurities entering the weldpool, but does not eliminate the problem, thus setting an intrinsic depth limit to SMA welding at around 300 m. (Reference 8)

One of the most favorable characteristics of SMA welding over GTA and GMA is that considerably less technical knowledge is required to achieve optimum performance in deep waters. However, since the SMA process with low hydrogen electrodes tends to produce marginally acceptable roots in open butt joints, the GTA process is generally used for the root bead and increasingly for the hot pass and first fill pass also.

3.2.3 FCA Welding

FCA welding, because it permits speedy welding, is widely used by those with access to a suitable consumable. A significant advantage of FCA welding over SMA welding is demonstrated in Figure 3-2, which demonstrates how there is significantly less hydrogen absorbtion into the weld metal with FCA welding.

3.3 Environmental Control of the Habitat

To attain satisfactory weld properties, the habitat must be dry and environmentally controlled for temperature. To dry the habitat, seals are created at each junction with the structure. The water is then excluded by gas pumped into the habitat and electrically operated environmental control equipment mounted in the habitat wall is then used to heat and dry the area. (Reference 16) One environmental control system currently being marketed consists of a circulation system of two blowers that passes the atmosphere continuously through a carbon dioxide absorber, a water vapor absorber filled with molecular sieve drying agent and different catalyzers for hydrocarbons, nitrous gases, carbon monoxide and hydrogen reduction. This system can absorb a heat load of up to 50 kw generated mainly by the welding in the chamber

The pressure inside the chamber is equal to the hydrostatic pressure of the particular depth. The use of air

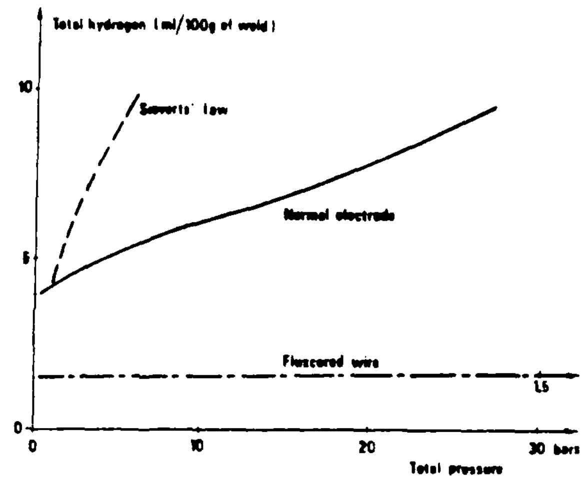


Figure 3-2 Hydrogen Content in Weld Metal vs. Water Depth
(Reference 15)

is, however, limited by the partial pressure of oxygen. One limitation used by some is that of 70 m, beyond which there is a risk of oxygen enrichment effecting an alteration of the lungs and the nervous system. (Reference 13) Pressure also intensifies the noxious effects of carbon monoxide, carbon dioxide, and ozone on the body. The other significant consideration with increased oxygen partial pressure is the increased flammability of the environment. At a depth of only 46m, clothing burns in air at six times the rate of burning at atmospheric pressure. In the opinion of one source (Reference 9), compressed air is not a safe working environment even when the depth exceeds only a few feet. My personal conversations with experts in the field indicated that compressed air was routinely used in welding tie-ins at depths of around 50 feet.

Apart from the danger to the diver of fire, contamination by air can have a devastating effect upon The soundness and mechanical properties of the weld metal. The SMA welding process uses carbon monoxide and carbon dioxide as shielding gases. These protective gases can easily be produced by the calcining of chalk, crushed marble or limestone included in the flux. Alternatively, or in addition to the lime, cellulosic materials may be added, which produce similar gas as they burn at the electrode tip. Estimations of the volume of shield generated by the melting and burning flux of a typical SMA welding electrode is about equivalent to a CO_2 gas flow of 12 litres per minute.

The effect of pressure in shrinking the size of the SMA welding protective gas shield is very marked and becomes evident even at a depth of only a few meters. At a depth of only 10 m the equivalent gas shield flow rate is reduced to about half so that even at this shallow depth, lack of adequate protection may begin to show its effects. Failure to maintain an extremely short arc under hyperbaric conditions have resulted in severe escalations in nitrogen content resulting in large reductions in charpy V energy. The very short arc length necessary to preserve shielding in an atmosphere of nitrogen, even under only slight hyperbaric pressure, can only be maintained in positional welding with extreme difficulty. (Reference 9) Additionally, it has been shown that at 40 bar a change in arc length of only 1mm will entail a consequent change in arc voltage of 3 volts with significant transient effects. (Reference 7)

For the above stated reasons, hyperbaric welding in habitat environments of nitrogen and oxygen are not usually recomended. For dry habitat welding repairs at depths beyond 17m of seawater, helium or argon based atmospheres with controlled oxygen levels are preferred. (Reference 14) From the aspect of the achievement of weld deposits of excellent mechanical properties, the provision of a pure noble gas atmosphere is effective; however, the performance of some welding electrodes is impaired by the absence of oxygen. Welding electrode fluxes are designed to work in air and normally contain large additions of ferro alloys, the purpose of which is to combat oxidation and to supplement some of the alloy content, such as manganese, which may be lost thereby. In the absence of oxygen, undesirable changes in the properties of the slag may result, leading to changes in mobility, viscosity, detachability and chemical composition. Sometimes these effects can result in poor weld coverage, leading to bad weld shape and difficulties in handling. Adding a small dose of oxygen to the shield, the amount dependent on the pressure, has been found to overcome these problems. (Reference 9) Despite the use of the inert atmospheres in hyperbaric welding, the danger of hydrogen cold cracking is still present from the hydrogen present in the chamber and in the electrode flux in the form of moisture.

3.4 Hyperbaric SMA Electrodes

It becomes readily apparent that most electrodes one may use under normal atmospheric pressure conditions cannot be used under the hyperbaric pressures experienced in the repair of underwater platforms. The effect of pressure on welding characteristics limits the size of the electrode and type fluxes suitable for use under high pressure conditions.

3.4.1 Weld Bead Geometry

Due to the pressure effects on the characteristics of the electric arc, the electrical variables of welding are also similarly affected by a modification of the physical properties of the plasma. This results in a change in the geometry of the weld bead made under pressure. In one study conducted on beads made in the flat position with E7018 electrodes, the geometry of the bead was shown to be altered by pressure, in particular in the range corresponding to a depth of 50 m. (See Figure 3-3)

3.4.2 Electrode Diameter

In vertical up welding, test results showed that the electrode diameter as well as the type of covering are important factors that may increase the changes in bead geometry. It appears that raising the arc temperature increases the fluidity of the molten pool and alters surface tensions, thus making electrode diameters above 3.5 mm (1/8 inch) practically useless. Selecting the proper electrode diameter becomes a determinant in avoiding defects such as porosity and slag inclusions.

3.4.3 Consumable Covering

Contrary to what happens at atmospheric pressure, for a same class of electrodes, the composition of the covering becomes an essential variable that may determine the usability of the electrode under hyperbaric conditions. (Reference 13)

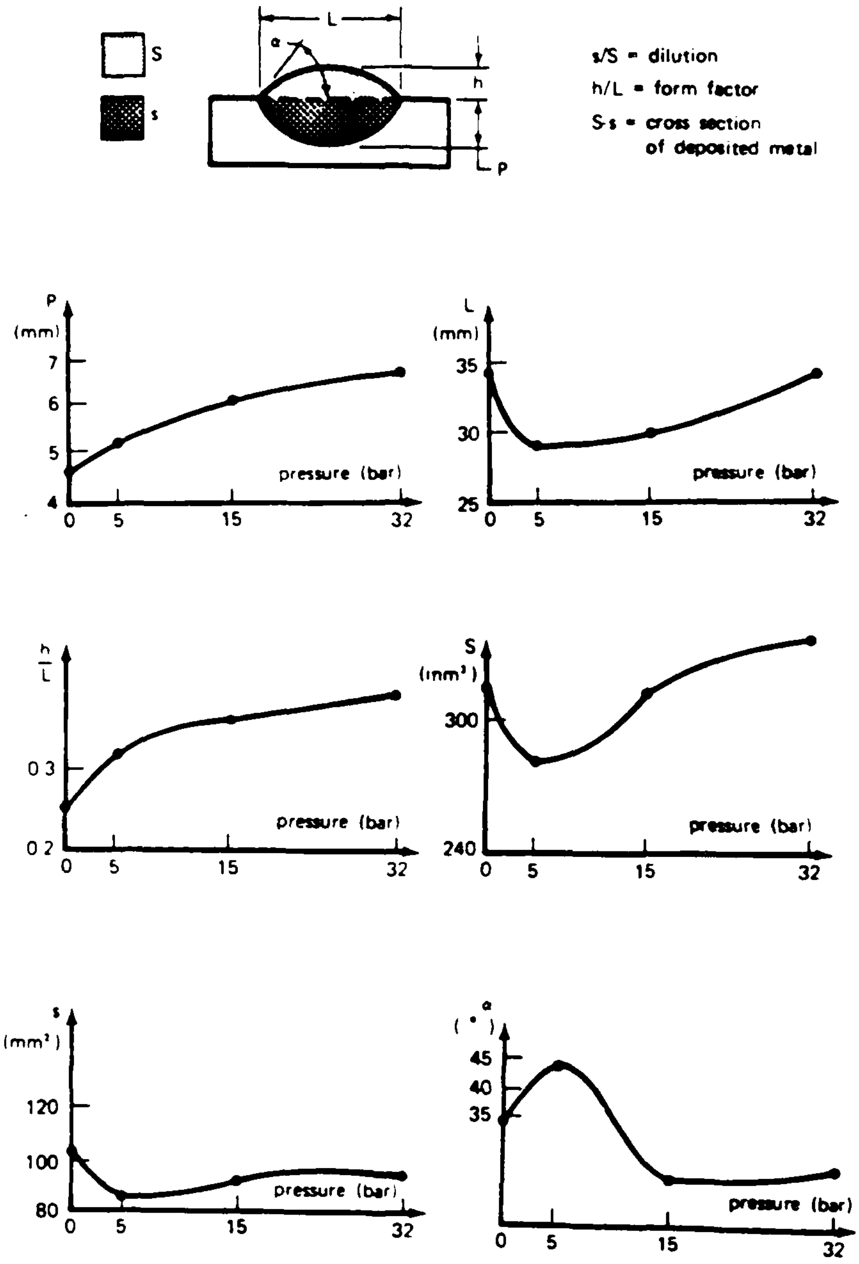


Figure 3-3 Geometry of Weld Bead in Flat Position
(Reference 13)

Many SMA electrodes which work well at atmospheric pressure perform so badly at even moderate hyperbaric pressure as to make them unusable. As pressure is increased, problems begin to be encountered, such as short circuits, arc outages, etc. Welding may become increasingly dificult, resulting in deterioration in appearance and impossible slag detachability. As depth exceeds about 150 m,, problems with weldability, especially for all position welding, may necessitate a progressive reduction in electrode size until the maximum usable size reduces to 2.5 to 3.25 mm. This restriction, leading as it does to further reduced current and hence thermal input, compounds the hydrogen cracking problem, making preheat and control of interpass temperature even more essential. One rough guide was, because of the total effect of these variables, was to increase the preheat about 100 degrees C over and above that which would have been required for the same sized weld at normal atmospheric pressure.

Many welding contractors use proprietary consumables that enable them to minimize undesirable features. Reference 15 documents the success one contractor had in attaining significant improvements in welding consumable characteristics. The electrode they developed, when welded under hyperbaric conditions, in addition to restoring some of the impact properties, showed a low carbon content, was less hygroscopic, had better handling characteristics and a readily detached slag. The improvement in their electrode performance over conventional electrodes is provided in Figures 3-4 and 3-5. This figure also shows the increase in gaseous absorbtion with pressure. The opinion of this contractor was that, while weld characteristic at 300m are perfectly adequate for all the major pipe welding specifications, comparison with results at 150m suggests that impact properties of the weldment would not be achieved at depths significantly beyond 300m if low Ni content electrodes are to be used. (Reference 11)

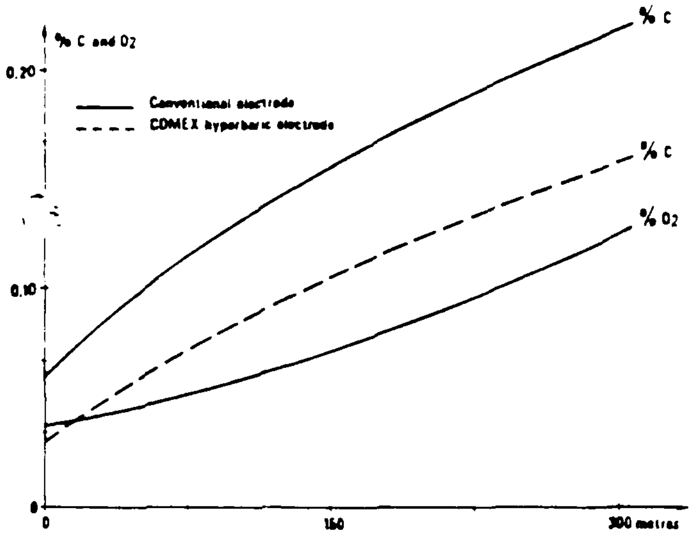


Figure 3-4 Weld Metal Composition vs. Water Depth for Typical Low Hydrogen Electrode (Reference 15)

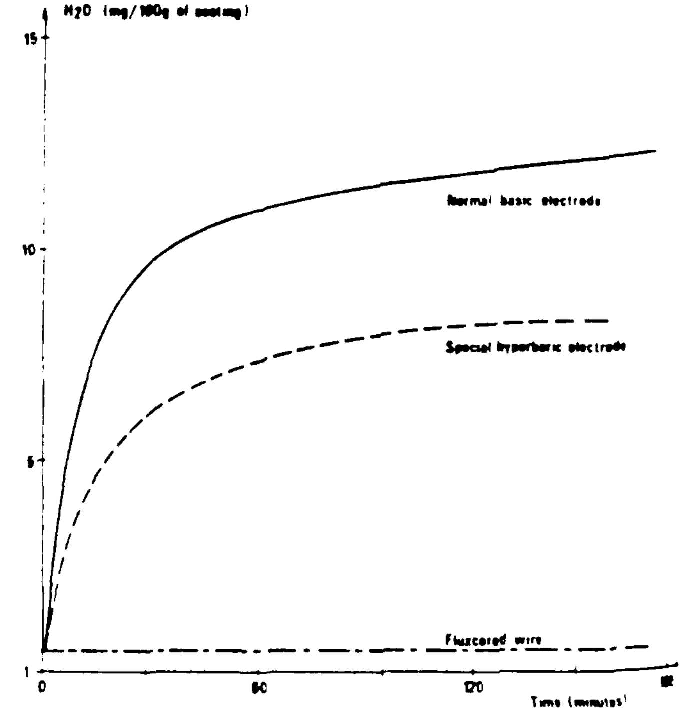


Figure 3-5 Moisture Absorbtion of Low Hydrogen Electrodes (Reference 15)

3.5 Hydrogen Cracking of Underwater Welds

3.5.1 Increased Hydrogen Absorbtion

Due to the fact that the ambient pressure influences the rate of atomic hydrogen absorbtion into solution in the molten weld pool (See Figure 3-6), the effect of hydrogen from whatever source, e.g. moisture in the flux coating, high humidity, hydrocarbon deposits, etc., is more marked under hyperbaric conditions and explains the increased susceptibility to cold cracking of welds performed under

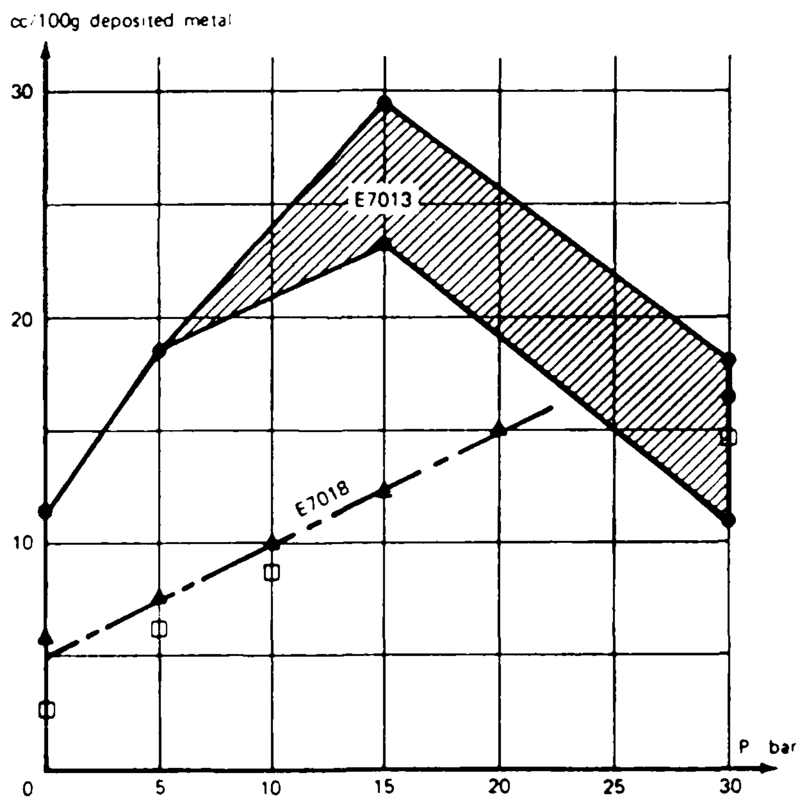


Figure 3-6 Diffusible Hydrogen vs Pressure (E7013 and E7018)
(Reference 13)

hyperbaric conditions. Increased hydrogen absorbtion in hyperbaric welds has been reported in numerous research studies. (Reference 8). One investigator reported that an increase in pressure from 1 bar to 8 bar was accompanied by an increase of hydrogen of two or three times (independent of the dampness of the electrode flux). The significance of nearly doubling the hydrogen content of SMA welding deposits, even at a depth of only 60 m, is of the greatest importance to those considering the use of this process for the welding of thick steels, especially when the steels are of comparatively high carbon equivalent. (Reference 6)

In addition to the increased solubility of hydrogen at higher pressures, another rationale has been presented to explain the increased concentrations of hydrogen at increased pressures. One of the effects of the changes in heat distribution between cathode and anode as pressure increases is that the proportion of the heat developed at the anode increases. Perhaps as a consequence of this phenomena, the droplet size decreases and the droplet frequency increases. The increased surface area of the total sum of the droplets together with perhaps the longer time they spend in the arc atmosphere is proposed as an explanation for the increased hydrogen absorbtion. (Reference 6)

The increased susceptibility to hydrogen cracking is illustrated by Figure 3-7 which shows that the critical cracking stress decreases as the pressure rises.

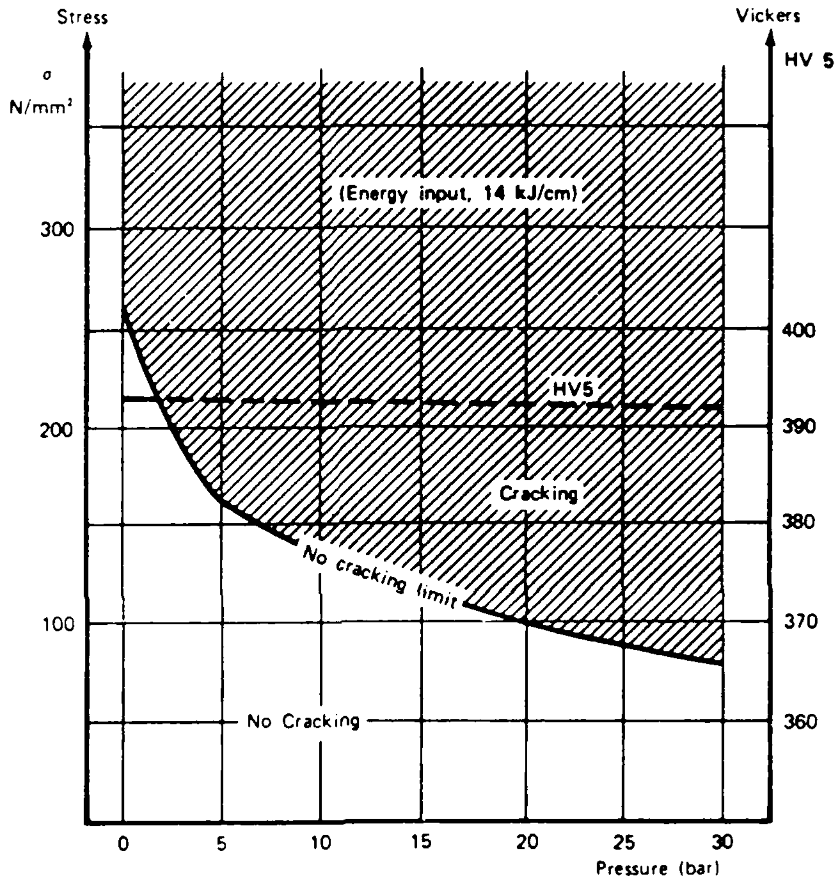


Figure 3-7 No Cracking Limit vs Pressure
(Reference 13)

3.5.2 Prevention of Cold Cracking

An analytical/empirical system for preventing cold cracking in steel weldments has been developed by a group of Japanese researchers and is presented by Masabushi in Reference 1. They propose the following relationship:

$$P_w(\%) = P_{CM} + \frac{H}{60} + \frac{Ks}{40{,}000}$$

where: $P_w(\%)$ = cracking sensitivity of the weldment

P_{CM} = Carbon equivalent (JIS)

H = diffusible hydrogen per 100 grams deposited weld metal ($cm^3/100$ g)

K_s = intensity of restraint of the joint (kg/mm^2)

Once the cracking sensitivity is determined, this can be related to critical cooling times, pre- and postheat temperatures.

Essentially, this formulation says that the contribution that hydrogen makes towards cold cracking in the welding of structural steels can be expressed in terms of:

The effective increase in carbon equivalent

(equals)

$$\frac{\text{the diffusible hydrogen in the weld metal}}{60}$$

The English researcher, Allum, has come up with a similar formula for establishing a cracking parameter. (Reference 6)

These formulations indicate that the effect of a small increase in the hydrogen content of the deposited weld metal can have a severe effect upon the cold cracking propensity of a typical weld connection. The difference in the reported hydrogen content of SMA welds made at 1 bar and at 8 bar is equivalent in loose terms to an increase in the carbon content of the steel of about 0.1%. This difference is about equal to the range of carbon content between the least weldable and most weldable structural steels in common use today.

3.5.3 Pre- and Postheat

The prevention of hydrogen cold cracking depends upon many variables, including: the composition and carbon equivalent of the steel being welded, the quench rate, the hydrogen content of the weld metal and HAZ, the restraint stress, the steel thickness, the welding process, the thermal input, ambient and preheat temperatures, etc. These variables all interact and contribute to hydrogen cold cracking within one of the previously mentioned theories.

Whatever theory of hydrogen cold cracking is espoused, the resultant practice is that it has become normal practice, for the welding of structural steels of significant thickness, to use low hydrogen electrodes, to keep them dry, and often to preheat so as to facilitate the diffusion of hydrogen out of the joint while it is still warm. The extent to which these precautions need to be applied will, of course, vary with the application. For most underwater welding jobs on offshore platforms mentioned in the literature, preheating has been applied. (Reference 6) (Note: One of my conversations with an expert in the field indicated that the application of preheat is not as widely practiced by Mexican welding contractors as it is by US and North Sea contractors.)

Preheat temperatures are generally higher and welding consumable control is more stringent than for conventional atmospheric welding. Additionally, post weld hydrogen diffusion treatments have sometimes been specified, typically at 200-250 degrees C. to reduce the level of hydrogen in the joints (Reference 14)

Preheating to high temperature is not always favored by welders confined in the small space of a habitat and surrounded by the heavy atmosphere of a compressed gas. An alternative to preheat has sometimes been to increase the thermal input of the welding arc. (Reference 6)

3.5.4 <u>Humidity Contribution to Hydrogen Absorbtion</u>

The contribution of humidity to the hydrogen that eventually will cause hydrogen cracking in hyperbaric welds becomes significant under certain conditions. It would be expected that higher hydrogen contents may be expected when welding in a humid habitat, due to moisture absorption in the electrode coating and to direct absorbtion into the exposed annular surface of the weld pool. This is supported by the work of Berthet and Gaudin (1976) which showed that where the critical stress attained was slightly more than one-half the yield stress in surface welding, the stress limit in hyperbaric welding was about 15% of the yield stress in a fairly dry atmosphere, and zero at saturation. (Reference 8)

The process of hydrogen absorbtion into the weld pool can be analytically developed using vapour pressures, solubility factors, and reaction temperatures to yield an effective hydrogen level. Using this analytical model and substantiating their conclusion with experiments, several researchers (References 6 and 8) have demonstrated that direct absorbtion of hydrogen from the ambient humidity is not a major contributor to the hydrogen levels unless the electrode has been baked to a very low initial water content (which is the case in virtually all hyperbaric welding jobs).

The risk of increased hydrogen absorbtion must be assumed to be present in a humid habitat and is related to the time of electrode exposure, the relative humidity, and the initial water content of the electrode.

Reference 10 reports on "Moisture Absorbtion of Basic Electrodes Under a Pressure up to 33 bar". The authors develop a model for estimating the water content of electrodes on the basis of initial water content, vapour pressure in the habitat and the time of exposure of the electrodes. Their supporting premise is that water absorbtion is in the main controlled by diffusion of water into the coating. Their model predictions are as shown in Table 3-1

Pressure and humidity	Time of exposure, minutes									
	0.2	1	2	3	5	10	15	30	60	120
16 bar - 95%	0.00	0.09	-	0.20	0.28	-	-	-	-	-
16 bar - 70%	0.05	0.07	-	0.11	0.14	0.19	0.25	0.30	0.50	-
31 bar - 95%	0.12	0.15	0.19	0.25	0.28	0.40	0.46	0.75	1.04	1.73
31 bar - 70%	0.02	0.04	-	0.06	0.10	0.15	0.22	0.29	0.41	-
31 bar - 50%	0.01	-	-	0.03	0.05	0.10	0.10	0.15	-	-

Table 3-1 Water Absorbtion under Hyperbaric Conditions (wt %)
(Reference 10)

Tentative times of permissible exposure, based on this model indicate that very stringent electrode consumable control is required to prevent moisture levels in low hydrogen electrodes from exceeding specified levels. This is supported by the very stringent and exacting procedures of one welding contractor. Their procedure is to bag the electrodes by twos in plastic bags containing the dessicant, silicagel, which are opened just before the actual welding operation. The electrodes are thus exposed to humidity for less than two minutes. (Reference 15)

The humidity model presented seems pretty accurate. It was used to predict weld metal hydrogen contents obtained with as-baked and stored electrodes at various contents of moisture (see Figure 3-8) Analytical results were consistent with experimental data and indicate that as expected:

(1) As the moisture content of the electrode increased, so did the hydrogen in the welds

(2) As the pressure increased, so did the hydrogen in the welds

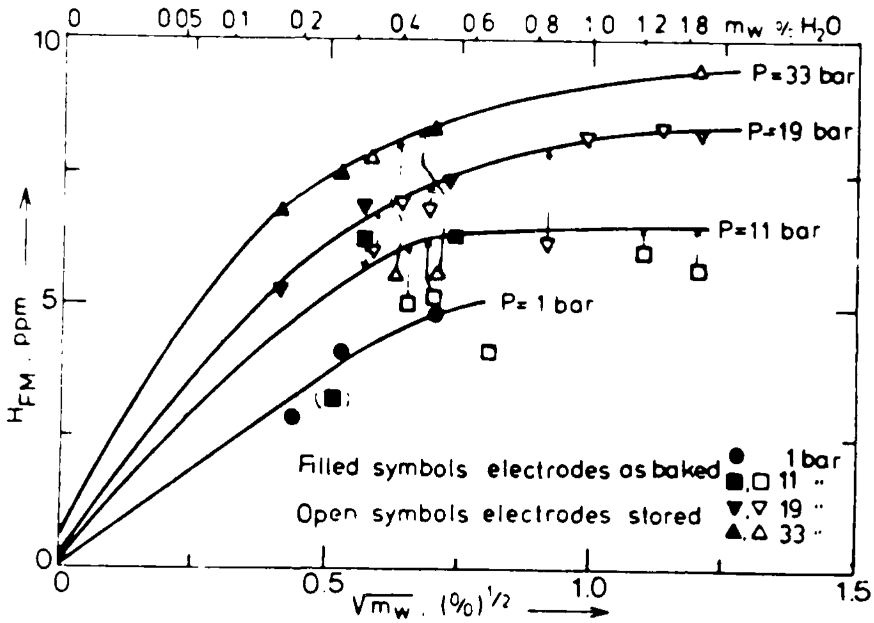


Figure 3-8 Hydrogen in Welds Deposited in a Manned Simulator (Reference 8)

3.5.5 Prediction of Weldability

It now appears that methods do exist for predicting hydrogen contents and for assessing their effect on safety against cracking. In addition to the model above for the prediction of hydrogen weld content, another model exists based on the Scandinavian concept of implant rupture stress R_{IR}. Linear relationships are developed between R_{IR} and log H_{FM}. If the linear relationship between R_{IR} and log H_{FM} is known for the steel to be welded, the weldability index can be interpolated for the expected absorbtion of hydrogen. (Reference 8)

3.6 Pressure Effects on Weld Metal Chemistry

Hyperbaric welding is characterized by the effects of pressure, which strongly influence the weld metal chemistry, and result in welds containing differences from equivalent welds produced at the surface. The general topic areas where the effects of pressure can be seen are:

A. Increased impurities

B. Gas density effects altering the heat exchange relationships and cool down rate

C. Welding arc effects

3.6.1 Increased Weld Impurities

When welding is performed under pressure, reactions consuming gaseous species will be favoured, and those producing gaseous products will be suppressed. Important representatives of such reactions are the increased absorbtion of hydrogen from the arc atmosphere, and the reduced evolution of carbon monoxide shielding gas. In both cases the impurity levels of carbon, oxygen and hydrogen will increase with increasing pressure, carbon being considered as an undesirable element in hyperbaric welds. Increased contents of oxygen in the metal will result in heavier losses of silicon and manganese during cooling. (Reference 8)

A major contributing factor to the increased absorbtion of gases is that the solubility of gases in the molten metal increase as a function of pressure. Percentage of gases entrapped for typical weldments as a function of the depth of the weld are indicated in Figure 3-9.

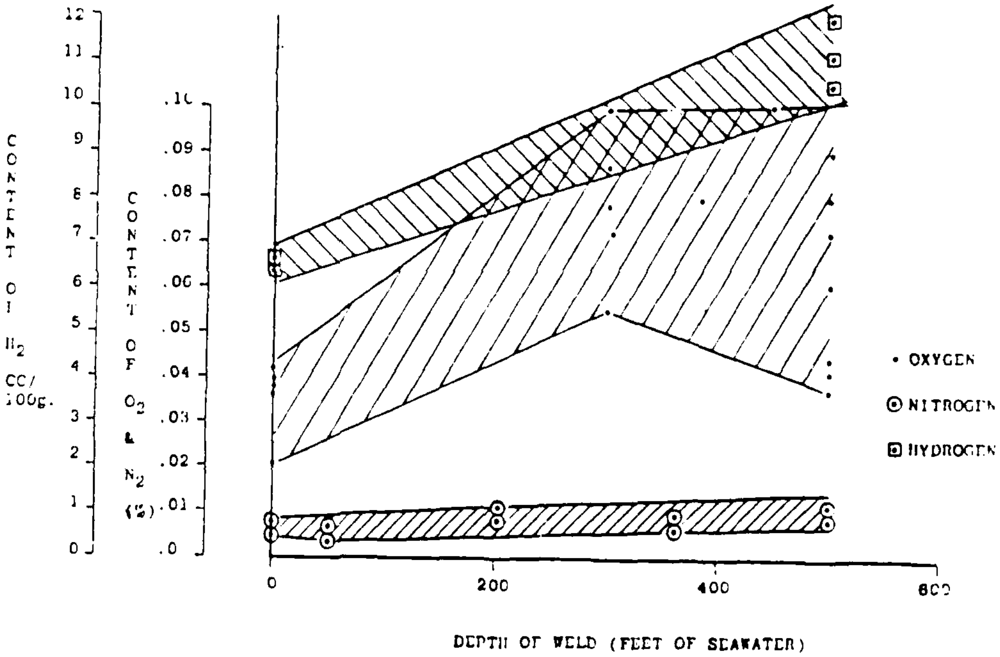


Figure 3-9 Variation of Gas Content with Depth (Reference 16)

The fact that oxygen and carbon concentrations in the weld metal increase with increasing depth is a genuine hyperbaric problem, because high concentrations of both elements are not encountered in surface welding. Studies have revealed that this problem results in a steady deterioration of toughness with increasing depth. (Reference 8)

An important source of the carbon and oxygen is from the decomposition of the lime/calcium carbonate coating of the low hydrogen electrodes used in SMA welding. When the arc is struck, the calcium carbonate contained in the electrode flux dissociates as follows under the effect of pressure, due to the rarefaction of the atmosphere in oxygen:

$$CaCO_3 \rightleftharpoons CaO + CO_2$$

$$CO_2 \rightleftharpoons CO + 1/2\ O_2$$

$$CO \rightleftharpoons C_{(\gamma)} + O_{(\gamma)}$$

(Reference 15)

The reaction tends to be toward incomplete combustion and formation of carbon monoxide, which decomposes into soluble carbon in the iron and oxygen. The increase in oxygen levels directly contributes to reduction in oxidizable elements such as manganese and silicon. This results in a shift of both the ductile/brittle transition temperature, the impact strength, and more generally in a loss of toughness of the weld. (Reference IId) The increase in carbon content and the resulting adverse effect on impact properties is illustrated in Figures 3-10 and 3-11. Welding rods were AWS type E8018 electrodes.

The increased availability of oxygen and nitrogen from the pressurization of the normal atmospheric constituents only makes the reduction in toughness and elongation and the susceptibility to weld metal cracking worse.

Another important factor is hydrogen coming from the humidity in the enclosure (around 60 to 100%) which can contaminate the electrodes and the weld metal. As previously stated, under pressure, the liquid iron or iron in the gamma phase is able to absorb more hydrogen than at atmospheric pressure, resulting in a lower cracking threshold in the HAZ under the weld.

3.6.2 Gas Density Effects

The increased gas density as a result of the pressurized environment, combined with the use of inert gas for the ambient environment in the habitat significantly alters the heat-transfer relationships. The magnitude of this change is illustrated by the tabulation of selected properties such as density and transfer coefficients illustrated in Table 3-2.

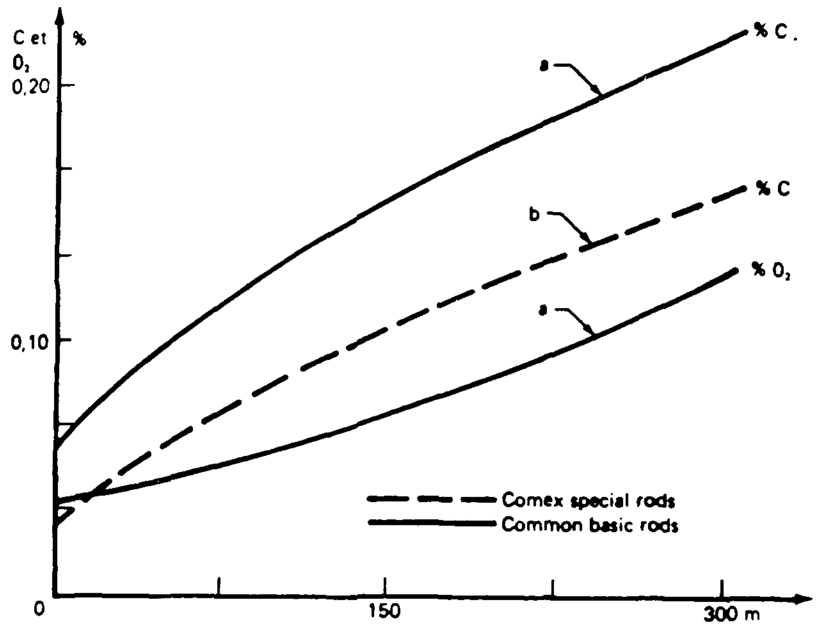


Figure 3-10 Carbon and Oxygen content in Weld Metal vs Depth
(Reference 11)

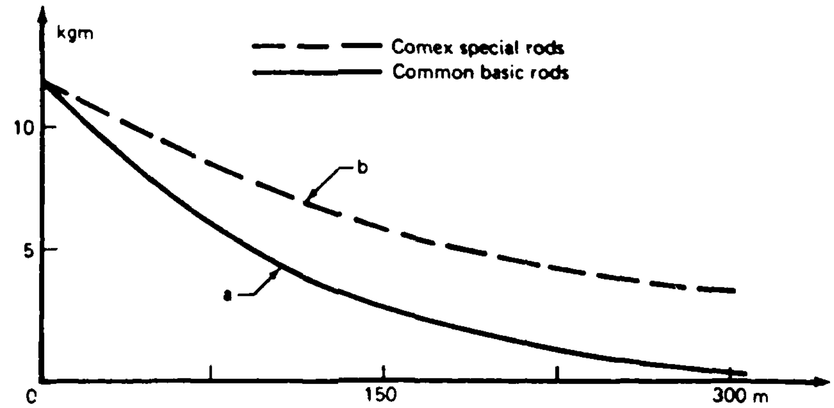


Figure 3-11 Impact Properties vs Depth
(Reference 11)

PROPERTY	DEPTH (FSW)						
	SURFACE	100	200	300	600	1000	1200
DENSITY (ρ) -lb/FT^3	.075	.085	.123	.136	.279 .215	.326	.388
SPECIFIC HEAT (C_p) BTU/lbm°F	.241	.401	.76	.410	1.1	1.167	1.168
OVERALL HEAT TRANSFER COEFFICIENT (U_o SIMILAR CONDITION) BTU/HR FT^2 °F	3.86	34.6	45.2	74.6	105.6	117.5	130.6
COMFORT CONDITIONS	75°F 55% RH	78°F 55% RH	80°F 55% RH	82°F 55% RH	85°F 55% RH	87°F 55% RH	89°F 55% RH
WATER CONTENT OF THE GAS (W) LB H_2O/LB dry mix	.01086	.00847	.00610	.00618	.00419	.00291	.00387

Table 3-2 Variation of Gas Properties with Depth (Typical) (Reference 16)

For considerations given previously, helium based atmospheres are used in most deep hyperbaric welding jobs. The helium, while it is an inert bas, has a thermal conductivity six times greater than air. Studies by researchers have indicated slightly shorter cooling times in high pressure helium than in air. This greater cooling has little effect on HAZ microstructures, but has an effect on the retention of hydrogen in the HAZ detrimental to weld quality. The reason the shorter cooling times do not adversely effect HAZ microstructures is because in the thickness of metal normally welded, most of the heat flows by conductivity into the metal rather than by convection into tne atmosphere. Thus the hardness in the HAZ will be very close to that measured in welds performed at atmospheric pressure with the same energy input. (Reference 15) The problem remains of the retention of hydrogen in the HAZ. It is generally acknowledged that the production of structural quality welds in the underwater environment requires that the heat input and quench rate be controlled. Such is able to be accomplished by adjustments in heat input; by variations in the consumables; and by pre- and postheating of the metal to be welded. (Reference 15)

3.6.3 <u>Welding Arc Effects</u>

A welding arc is a sustained electrical discharge through a high temperature, highly electrically conductive column of plasma and is produced by relatively large current and low voltage. Welding arcs in air are constricted to some extent by electromagnetic forces. An underwater welding arc is additionally compressed by external forces, pressure, and cooling effects. In order to maintain the rate of current transfer, core temperatures must increase. The very high arc-core temperatures found at greater depths increase penetration. For electrode positive SMA welding, more heat is gradually generated at the electrode tip as depth is increased, and less at the cathodic molten pool. The welding process, in terms of deposition rate, becomes more efficient with the speed of welding increasing by as much as 30%. However, such a weld will be significantly colder than its atmospheric counterpart. (Reference 6) As depth and hydrostatic pressure increase, the current density of the arc increases and therefore a higher voltage is required to maintain a constant arc length. (Reference 7)

It has also been observed that the preferred polarity may change with pressure, i.e. electrode negative GMA is preferred to electrode positive beyond about 7 bars. Consumable arcs have a substantially higher fall voltage than GTA arcs and so most power generation remains at the electrodes with increasing pressure. Calorimetric tests on SMA welding have confirmed that process heat transfer efficiencies are little influenced by pressure. (Reference 9)

Increasing pressure also causes electrode burn off rates to behave in a complex manner. For electrode positive solid wire GMA and FCA the burn off is substantially independent of pressure. However, in electrode negative GMA the burnoff rate falls such that the value at 7 bars can be less than half the normal ambient value. For SMA welding in the electrode positive mode, increases in burn off of 30% have been reported over the first 4 bars. This has been associated with a redistribution in arc heating such that more power appears at the rod and less at the plate. In electrode negative GMA welding, behavior can be such that the burn off initially increases reaching a peak between 2 and 3 bars before falling to a level below that observed under normal ambient conditions. (Reference 9)

The constriction of the arc and of the volumetric shield surrounding the arc results in a decrease in arc stability. Because of the reduced arc stability, smaller diameter welding consumables (generally 2.5 and 3.2 mm) are required for hypeerbaric use than for surface applications. The effect of residual magnetism in the steel, whether caused by geophysical effects or induced by machining or grinding, coupled with the less stable arc often results in magnetic arc blow. It is frequently necessary to demagnetise before root runs are deposited.

3.7 Survey Results

A survey was conducted of U.S. actual underwater welding jobs performed on offshore structures. The survey was initiated to cover various subjects including:

(a) Welding processes and techniques. Which processes are used: "dry" or "wet"; shielded metal arc process or gas metal arc welding? Which techniques are used for butt joints or fillet joints?

(b) Details of welding procedures. Joint design, degree of restraint, residual stresses, preheating temperatures, and the range of humidity in dry hyperbaric welding.

A total of 89 survey questionaires (see Figures 3-12 and 3-13 for sample cover sheet and questionaire) were sent to persons interested in the field of underwater welding, as evidenced by their participation in a conference on the subject. Survey recipients included persons in the oil industry, welding contractors, various research institutes, government regulatory agencies, and academia. Unfortunately, most responses contained little information, as the respondent had had little actual experience in this field. Many oil companies referred me to their welding contractors. One oil company considered the information I was asking to be proprietary in nature. Of the 89 initial inquiries, only 10 substantive replies containing factual and useful information regarding underwater welding practices were recieved. These responses are summarized in this section of the report.

Most of the dry hyperbaric welds conducted have been done in the North Sea. This is in large part because the regulatory bodies for the offshore platforms (either Lloyds (British) or Det Norsk Veritas (Norwegian)) almost invariably require that welding repairs be done "dry". A consideration that may have resulted in the above statement is that most North Sea platforms have carbon equivalent values greater than 0.40. These carbon equivalent values preclude wet welding due to predictable joint hardness and low impact values. Because wet welds, clamps , or other repair methods have been shown to be adequate for the repairs conducted in the Gulf of Mexico, dry hyperbaric welding has not been as commonly used.

The Minerals Management Service is the regulatory agency for the offshore oil and gas industry. Their policy is that they do not conduct or specify any specific underwater welding technique. However, in most instances, mojor underwater repair programs must be approved under their Platform Verification Program.

Hyperbaric welding will invariably give better weld quality results than wet welding. This is not to say that wet welds are bad. A wet weld, properly done can meet all the strength and integrity requirements that a dry weld can. It is just important to know its limitations. A wet weld will probably be much bigger than the same weld, had it been done in the dry. It will probably have a higher degree of evenly distributed porosity. It will have a harder HAZ, be less ductile, and is not suitable for highly stressed joints subject to fatigue. The main reason wet welding is not used in the Gulf of Mexico is that it is too expensive. The cost differential between a dry weld and a wet weld to do the same job has been estimated as between 3:1 to 8:1. If a cheaper method to conduct repairs exists, that results in a satisfactory condition, then the cheaper method will invariably be used. The following rough cost example is provided to illustrate the cost differential.

Problem: Repair of offshore structure requiring a strengthening member be reinforced

Wet weld: 12 inch brace. 5/8 inch weld. Cost = $20k solution

Dry weld: 10 inch brace. 1/2 inch weld. Cost = $65k solution

The lack of usage of welding in general for the repair of offshore structrures in the Gulf of Mexica is evidenced by the responses to my survey from two offshore oil companies which said that they had had no underwater welding (wet or dry) performed on its offshore pipelines and platforms. Another offshore oil company replied that it had had only one welding job performed on one of its offshore platforms, and that it had been done wet.

In the words of one respondent to my survey:

> "(respondent) typically avoids welding below water. When adding appurtenances to structures or making repairs to damaged structural members, we generally utilize bolt-on clamps. We have found this to be more cost effective and just as reliable as welding."

Another respondent wrote:

> "...hyperbaric welding is not often employed in the Gulf of Mexico for structural repairs. In fact (respondent) has not used hyperbaric welding on any of our 320 structures. Our primary method of structural repair is wet welding new joint configurations. Of course the weldment is not as high quality as can be obtained from hyperbaric conditions, but with proper design, we can obtain a joint configuration that can sustain the loading conditions at a fraction of the cost of hyperbaric repairs. There is always the possibility that a situation may arise in the future where hyperbaric welding may be the most prudent method."

Note: I have subsequently learned that this company is presently planning a hyperbaric welding job on an offshore platform to be conducted at a depth of approximately 600 ft.

The structural integrity of the platform was involved and the depth of the repair prohibited wet welding.

Depth considerations certainly constrain the use of wet welding. Wet welding is usually limited to a depth of approximately 190 feet. However, one contractor did qualify a weld to 325 feet in bidding for a contract (only one of five contractors to do so). Should welding be required below this limiting depth, it would have to be done in a habitat.

Respondents to my survey estimate that approximately 80% of the underwater welding jobs done in the U.S. are conducted in the wet. Most of the dry welds are for "hot taps", which are where one pipeline has to be connected to another pipline. Structural integrity considerations necessitate a dry weld. These hot taps have normally been done in relatively shallow water (approximately 100 ft.)

The welding processes used by most contractors and oil companies include GTAW, GMAW, FCAW, and SMAW. My sense was that the most popular technique was the GTAW root pass followed by the SMAW fill passes. As in the literature survey, those companies using GTAW didn't use GMAW, and vice versa. One company indicated that it limited SMAW to depths less than 250 feet.

In personal conversations with some of the survey respondents, they indicated only slight changes in the welding parameters (current and voltage) used during underwater welding. This was not supported by my research.

but may be due to the fact that I was welding at higher pressures than they were used to. Other respondees indicated that higher amperages were required.

Those contractors using SMAW for the root pass used 3/32 inch E7016 electrodes for the root pass followed by 1/8 inch E7018 electrodes for the balance of the passes. GMAW was used for butt welds by one contractor. GTAW seemed to be the preferrrential process for the root pass.

The electrodes recommended to me were CHEMTRON and ATOMIC ARC E7018. These rods proved better than the KOBE Steel electrodes I had been using with respect to bead characteristics, but were much worse than the HOBART E7018 electrodes I eventually chose.

One contractor stated that he always used at least 100-150 degree F. preheat to get the moisture off the steel. He mentioned that in jobs he was familiar with in Mexico, that they did not use preheat.

Explanations offered for the very erratic arc and weld bead distribution I was getting for the earlier electrodes I was using were:

(a) oxygen contamination of the shielding gas

(b) incorrect amount of CO_2 in the shielding gas

(c) due to my using pressurized atmosphere instead of inert gases, and that I should at least use a cover gas of Argon.

Contrary to what was said in the literature about not using nitrogen atmospheres in habitats due to nitrogen contamination of the welds resulting in severe reductions in Charpy V energy, two of the contractors I spoke with indicated that they routinely used nitrogen as a habitat atmosphere. The main reason for using the nitrogen was its low cost compared to using argon or helium. When questioned as to the deepest one contractor would use compressed air as a habitat atmosphere, he replied "about 100ft".

When questioned obout humidity. One respondent described the humidity condition as a 'dripping wet' 80 to 100% relative humidity. Another respondee indicated that the worst case condition of 90% humidity was assumed for welding conditions, but that actual humidity conditions were much less. I feel that this would be a direct reflection of the habitat environmental control system and would vary from habitat to habitat. The range of responses for humidity varied from 70 to 95%.

No respondee gave a factual number for restraint. Those that did address this subject indicated that the restraint would be dependent on the geometry of the weld joint, and would vary for each specific situation.

IV. METHODOLOGY

The conduct of this thesis required being able to model the welding conditions experienced when conducting underwater welding under hyperbaric (dry) conditions. These welding conditions are routinely experienced when welding repairs are made to deep sea oil drilling platforms. It became readily evident that what was required was to design a remotely operated automatic voltage controlled shielded metal arc welding device for use in a hyperbaric chamber. The Ocean Engineering Department welding lab already had a hyperbaric chamber capable of being pressurized to 300 psig. The remaining materials and equipment had to be procured.

4.1 Equipment Setup

A general description of the welding setup is as follows. The desired goal was to conduct stick electrode welding remotely in a hyperbaric chamber. An automatic arc length control welding device is used to control welding voltage and thus arc length. Although this apparatus is normally utilized for GTAW, by substituting a SMAW electrode for the tungsten electrode in a specially procured Heliweld machine holder, the described equipment can be used to properly vertically position the SMAW electrode by controlling arc length. Motion of the weld bead along the test samples is accomplished by moving the test sample. A variable speed motor carriage attached to a cart fabricated to carry the sample was assembled to accomplish this. A sensor switch can be actuated upon achieving the desired weld bead length to shut off the welding power supply. (NOTE: What would be more desirable, would be a gradual lowering of arc current, but this was not achievable due to malfunctions in the current equipment.) In practice, the sensor switch was not normally used, because it was equally easy to just turn off the power upon observing the arc reach the desired point at the end of the welding run.

Materials used to complete this project were:

- Jetline Engineering Model ALC 101 Automatic Arc Length Control welding device
- Heliweld Model M50 A Machine holder
- Variable speed electric carriage
- *Welding sample carriage tray
- Pressure chamber
- *Pressure chamber extension
- *Welding connection to weld head
- Ultrasonic humidifier
- Air Compressor
- Wet and dry bulb thermometers
- Fan

Items denoted by an * were manufactured to my specifications. The welding sample carriage tray was designed to attach to the variable speed electric carriage.

Special accomodations were required to ensure that the tray was insulated from the pressure chamber and the electric carriage.

The ALC device is designed to be used with GTA welding. Thus there ore 3 connections to the welding head: a water supply, a water return, and the purge gas connection. Current is normally fed not only through the cable sheath of the water connectors, but using the conductivity of the water as a medium for electrric current. The setup for this experiament did not utilize either the purge gas or the water connections. In order to ensure an adequate conductive path for the current flow, a new connecter was made up of 0 sized cable to transmit the welding current to the welding head.

The pressure chamber used in this research is 6 feet (1.8 m) long and 30 inches (76 cm) in diameter. It can be pressurized up to 300 psig (2070 KN/m^2) simulating the water depth of 700 feet (210 m). Due to the large size of the welding apparatus, the pressure chamber required modification. An extension to the pressure chamber that fit onto one of the pressure chamber's sight glass windows was designed and manufactured.

Electrical connections for components internal to the pressure chamber were made utilizing interface connections designed into the pressure chamber or pressure chamber extension.

A purge system using argon gas was also devised for use with this apparatus. The principle used in this system was the fact that since argon is heavier than air, all you need to do is provide a blanket over the welding arc to provide the necessary inert gas atmosphere. Pressure tank connections existed that were able to be adapted to accomplish this setup.

As in all experiments, problems arose in utilizing the Jetline Automatic Arc Length Control Welding Device in that the device's remote and automatic features did not operate as designed. It was initially desired to set up the welding sequence such that all operations were automatically executed once initial set up and parameters had been established. In this case, it would have been accomplished by pushing the Sequence Start pushbutton. Some of the specific problems with the Jetline Automatic Voltage Control device which occurred were:

(1) The device was supposed to provide remote contactor control of the welding power supply to switch on and off current from the power supply to the electrode. This function did not work when connections were made to the proper amphenol connectors.

(2) A remote switch was to be actuated inside the pressure chamber to stop the welding sequence and power supply. When hooked up to the the proper amphenol connectors, this feature did not work.

(3) The Sequence Stop push button was supposed to down slope the current to the electrode, to avoid forming a crater at the end of a welding sequence when the current is abruptly shut off, and then to turn off the motor carriage. This feature did not work.

(4) The Sequence Start Pushbutton was supposed to automatically sequence the initiation of the welding arc and start of welding cart travel. This feature did not work.

(5) The utilization of the Jetline Automatic Arc Length Control was obviously not the specific use for which it was intended. Special fitting and weld cables had to be acquired and attached to permit successful operation. Possibly due to this "abnormal operation" and "unusual setup", problems arose with IC chips and transistors, which required troubleshooting and replacement.

During one period of abnormal operation, I could only achieve adequate results by hooking up the connections for the control of the remote welding power supply to the incorrect amphenol connectors. However, it was now necessary to use the Emergency <u>Stop</u> pushbutton to <u>energize</u> the relay to provide power to the electrode. The Sequence <u>Start</u> pushbutton now turned <u>off the relay.</u>

I achieved remote shut off of the power supply by bypassing the amphenol connector and attaching my leads from the remotely actuated switch in the pressure chamber directly to the Sequence Start pushbutton connections (which now when actuated would shut off the current to the electrode).

Most of the problems with the Jetline Automatic Arc Length control were eventually resolved, however by that time, I had already decided not to use the automatic start and stop sequencing functions of the sequence start and stop switches.

The final configuration provides remote control of SMAW welding in a hyperbaric chamber. The sequence of operations required to conduct one pass of welding inside the chamber is:

(1) Grind the tip of a new electrode to a fine pointed tip and insert the electrode into the electrode holder.

(2) Position the cart and workpiece below the electrode. Attach the ground to the workpiece. Clamp the workpiece to the cart. Ensure the workpiece is properly aligned by running the cart back and forth under the electrode tip several times.

(3) Position the remote switch to turn off the power supply at the end of the desired weld run. (optional) Turn off the external power supply switch to the motor carriage. Select the proper speed and direction of motor carriage run using the variable speed rheostat and direction switch on the motor carriage.

(4) Close the pressure chamber door and pressurize the chamber.

(5) Position the floodlight at one of the viewports to observe the interior of the pressure chamber.

(6) Turn on the fan to circulate air past the wet bulb thermometer. When the temperature stabilizes, observe and record the wet and dry bulb thermometer readings. Record relative humidity. Operate ultrasoonic humidifier as necessary to obtain the desired humidity.

(7) Turn on the control box.

(8) Set all controls on control box and welding supply to the desired settings.

(9) Ensure remote switch for the power supply is off and turn on the welding power supply.

(10) Vertically position electrode near the workpiece surface using the touch retract feature of the control box.

(11) Verify all conditions are established.

(12) Start an arc by positioning the remote switch for the power supply to 'on'.

(13) When an arc is established, start the cart to move the weld bead down the workpiece surface by turning on the external to the pressure chamber carriage power supply switch.

(14) When the arc is extinguished, stop the cart.

<u>OR</u>

Upon observing that the workpiece has reached the point where the welding rod is at the end of the desired weld bead run, turn off the welding power supply by using the remote switch for the power supply, and the cart by using the external carriage power supply switch.

(16) Deenergize the welding power supply and control box.

(17) Depressurize the pressure chamber, open the door and remove the welded sample.

A significant factor in the conduct of this thesis was the large amount of time required to conduct welding runs at pressure. Access to the pressure chamber is through a large swing out door that is secured using 30 one inch bolts. These bolts had to be properly positioned and then washers and nuts manually secured or loosened using a large and unwieldy impact wrench. This process was minimally improved by using a counterweight and pully system to offset some of the weight of the impact wrench. This part of the thesis was truly tedious, dirty, obnoxious and very time consuming. Even when proficiency was gained in bolting and unbolting, thirty to forty minutes were required to complete a bolting and unbolting sequence. Raising the pressure inside the chamber to 100/200 psig required an additional 30 to 60 minutes. This long process time to just <u>attempt</u> to conduct one welding run was the main reason why more data or more type samples were not conducted.

4.2 Parameter Selection

The vast majority of time spent on this thesis was in determining the correct methodology, parameters, and consumables required to obtain adequate results. This section will describe some of the attempts at achieving satisfactory results that were conducted. Hopefully this will benefit those individuals that follow me, and save them some efforts from repeating my mistakes.

4.2.1 Striking a Welding Arc

Since the apparatus used in this thesis was operated remotely, the manual dexterity afforded by an individual holding a welding rod and performing the intelligence based actions required to strike a welding arc were not available. It was readily apparent that some consistent mechanism of striking an arc was required. To conduct the laborious and time consuming process of equipment setup and chamber pressurization, only to find out that an arc could not be established would be very frustrating.

It was first attempted to use the touch retract feature of the automatic voltage control device to simulate the dynamic actions of a welder touching and then quickly retracting the electrode to establish an arc. This method worked some of the times, but was deemed too unreliable and inconsistent. The touch retract mechanism was probably too slow in retracting, and the contact phase was excessive, enabling short circuit conditions to exist for too long.

It was then attempted to place the electrode a fixed distance from the workpiece. This technique proved unreliable also, especially at higher pressures.

Steel wool was then placed between the electrode tip and the workpiece. This worked great at 0 psig, however, problems arose when going to higher pressures. Equipment setup and bolting the chamber door shut inevitably resulted in enough vibrations to cause the steel wool to move away from the welding electrode tip. Attempts to fix the steel wool to the tip with tape or glue proved futile. The attaching device would interfere with the current flow and subsequently the arc starting mechanism. Instead of generating an arc at the tip of the rod, the attaching material would burn. After the material had burnt through, if the geometry of the welding rod tip with the workpiece was satisfactory, a new impulse of current would result in arc initiation.

It was finally discovered that if the electrode rod tip were ground to a fine point, the workpiece surface oxide coating was removed, and the correct separation distance between the tip and the workpiece was established, that arc initiation would occur every time (provided, of course, that adequate amperage was provided).

4.2.2 Sensitivity Control

The sensitivity mechanism on the Arc Length Control (ALC) device controls how fast the ALC drive will respond to an arc voltage fluctuation or change. Having the sensitivity too high would result in overreaction to voltage fluctuations. Since these volltage fluctuations would normally occur on the high side, it would cause the rod to drive down into the weld pool. A setting of 'one' was finally decided on.

4.2.3 Touch Retract Control

The touch retract mechanism operates to properly position the torch electrode the proper vertical distance from the workpiece. It operates by sensing when the electrode comes into contact with the workpiece. The ALC drive will then reverse itself for a period of time dictated by the "touch retract" timer setting. Proper prepositioning of the touch retract mechanism was essential to get arc initiation. Having the electrode too far away would result in no arc initiation. Having the electrode too close would often times result in a very short lived arc, as the arc would start, but would extinguish itself as the rod would stick to the baseplate. The optimum touch retract setting varied with different surface geometries, i.e., under the same welding conditions of pressure, amperage and voltage -

the touch retract setting would vary between welding on a flat plate, Lehigh specimen, or Tekken specimen.

4.2.4 Voltage Setting

The voltage setting controlled the welding arc length. While it was desirable to have a short arc length for arc stability considerations, having the setting too low resulted in the rod sticking to the plate before completion of the welding run. Having the voltage setting too high would result in too long an arc. At high pressures, this would result in excessive arc instability and arc wandering.

Voltages would actually vary from within approximately 1 volt below the setting to up to 8 volts above the setting. If voltages ever exceeded the setting by "6" volts, the automatic arc length controller was supposed to cut off power to the electrode because it thought that it sensed a "burn-through" condition. A setting of approximately 23 volts was finally established as a workable setting. This setting sometimes had to be varied up to 0.5 volts to establish welding conditions that would result in an acceptible weld. It was noted that voltage fluctuations were generally more severe at high pressure conditions.

4.2.5 Amperage Control

Amperage control was adjusted to provide the best weld bead geometry, i.e., surface shape and characteristics, depth of penetration, bead width, etc. It was discovered that the manufacturer's suggested parameter of approximately 160 amps could not be adhered to at high pressure conditions. Very high amperages were necessary to initiate and sustain the arc

Control of volts and amps was regulated to obtain a satisfactory bead. While it would have been desirable to have a constant heat input for all welding conditions, and vary voltage and amperage to obtain this condition, this proved not to be practical. The voltage and current setting was completely predicated on having an acceptable weld bead. At high pressure conditions, this was acomplished by obtaining a voltage setting that would work with the highest amperage available.

4.2.6 Start Adjust Setting

The start adjust control on the welding power source permits the operator to select an amperage setting for arc initiationo which is different from the setting of the steady state amperage control. The starting current which is selected is in effect for the first 35 to 40 ccycles of the weld. After this time period, the weld current will go to the setting of the steady state amperage control.

It was found to be necessary to use a setting of 10 on the start adjust control dial. Use of lower settings did not provide as reliable results for initiating the welding arc. This resulted in the initiating arc current being 300 amps.

4.2.7 Welding Speed

Arc travel was accomplished by moving the workpiece under the stationary welding rod. Slower speeds than the manufacturer's recomended parameter were generally found to provide better weld bead penetration. Acceptable weld bead characteristics were obtained by using a speed of 7 inches per minute for all welding runs.

4.2.8 Electrode Baking

The welding rods used were 1/8 inch (3.2 mm) Hobart AWS 7018 electrode, which is a low hydrogen rod of a type commonly used for hyperbaric applications. Most low hydrogen rods specify a baking time for the rods to get rid of excess moisture. This should be followed by rapid use of the rods upon removal from the oven. This bake period was not utilized for these rods because it was not felt that the high humidity conditions present, in conjunction with the long delay times in setting up the apparatus and in establishing the desired welding conditions (45 - 75 minutes) would negate the beneficial aspects of baking the rods in an oven.

4.2.9 Preheat

Preheating of the workpiece was not conducted for two reasons. Worst case conditions that would most likely promote cracking were desired. In addition, the large electrical requirements of heaters could not be sustained through the existing pressure tight connections of the pressure chamber.

4.2.10 Final Settings

	Manuf. recom	0psig	100psig	200psig
Amps	150	220	280	280
Volts	short arc lgth	22.8	21.6	22.4
touch retract	---	2	2	2
Sensi-tivity	---	1	1	1
Arc (in/min) travel	---	7	7	7
Start adjust	---	10	10	10

4.3 Atmosphere

Atmosphere containing the normal percentages of oxygen, nitrogen, hydrogen, etc. was used in the welding chamber at 0 psig and for pressurization to higher pressures. The main reason for this decision was for convenience. Under normal offshore platform welding conditions, normal atmosphere is only used down to welding environments of around 100 to 150 feet below sea level (70 psig maximum). This is to prevent a highly flammable situation arising from the raising of the partial pressures of oxygen by pressurization and the contamination of the weldment with oxygen and nitrogen. Deeper than this depth, inert gas environments are used. Since the welding chamber used in this research was to be unmanned, and the effect of oxygen and nitrogen contamination would minimally, if any, affect the outcome of the research, it was decided to only use normal atmosphere for pressurizing the pressure chamber. It would have been extremely expensive to provide an inert atmosphere of heliox or argonox, even if a reclamation system could have been procured or developed. A local purge system utilizing argon gas that would blanket the weld was fabricated, but not used, as acceptable welds were obtained without its use.

The high flammability of the pressurized atmosphere actualy caused several problems during experimentation. In one instance, while at 200 psig, a spark landed on a teflon attachment to the sample cart and immediately caused the teflon to start burning. Rapid depressurization of the chamber to remove excess oxygen was insufficient to prevent complete incineration of the teflon piece. At 0 psig, the teflon piece had been totally immune to many welding sparks. Thereafter, copper sheets were placed over all plastic, wood, or otherwise flammable pieces in the pressure chamber to prevent this incident from recurring.

4.4 Humidity

One of the unavoidable problems associated with underwater welding under hyperbaric conditions is the presence of humidity. The exact amount ot humidity to be dealt with varies with the individual habitat system and its ability to control the environment, but has been estimated as being from 60 to 100%. Discussions with an underwater welding consultant indicates that the humidity conditions are "dripping wet". The humidity conditions I selected were:

dry: the ambient humidity conditions in the welding laboratory

humid: 100% humidity as indicated by equal readings on the wet and dry bulb thermometers in the welding chamber

wet: in addition to 100% humidity, the humidifier was left on for ten minutes. This created a condition where the ultrasonic humidifier was emitting a fine water mist, but where the air could not accept any more moisture. The water is forced to fall on the surfaces of the welding chamber interior.

An ultrasonic humidifier was used to help establish humidity conditions. At 0 psig, it was used to obtain the 100% humidity condition. At 100 and 200 psig, the 100% humidity condition was automatically established through the just completed pressurization of the atmosphere. Since the compressed air is less able on a percentage basis to retain moisture than at 0 psig, pressurization of air will inevitably lead to achieving a 100% relative humidity condition. Any subsequent pressurization results in condensation of excess water in the air. Should I have desired to establish a lower humidity condition at pressure, I would have been forced to wait extremely long times for the humidity to reach an equilibrium condition for the existing temperature and pressure. An alternative approach would have been to dry the tank by some means (dessicant or heaters). I elected not to do either of these options and just used 100% humidity at hyperbaric pressures. At 100 and 200 psig, the humidifier was used to establish the wet conditions desired.

4.5 Pressure Settings

It was originally intended to utilize the maximum capabilities of rhe pressure chamber and weld at 3 pressures - 0, 150, and 300 psig. However, while conducting studies to ascertain the optimum welding condition at high pressures, it was found that 200 psig was the maximum pressure that an arc could be established and sustained with the existing equipment. At pressures only minimally greater than 200 psig, i.e. 225 psig, either an arc could not be established, or arc initiation would be immediately followed by the arc going out, for reasons I could not ascertain. Upon lowering the pressure to 200 psig, and depending on the condition of the welding rod tip, a welding arc could be successfully established. It was therefore decided to just weld at 0, 100, and 200 psig. (Note: an option not fully explored would have been to use a smaller diameter welding electrode.)

4.6 Selection of Welding Rods

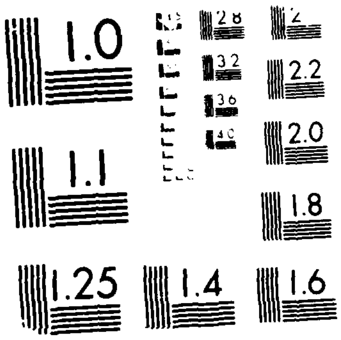
The process of selecting an appropriate welding rod to conduct this thesis with took up the largest number of manhours in the conduct of this thesis. The type of welding rod supplied by the sponsors of this thesis was a Kobe Steel manufactured low hydrogen type rod designated LB-52UL. This welding rod was originally supplied in 5/32 and 1/4 inch diameters. Field experience related to me through the literature search and correspondence resulting from the questionaire I had sent out indicated that as a minimum, obtaining satisfactory welds would probably require even smaller electrodes. It was then requested that Kobe Steel supply 1/8 in (3.2 mm) electrodes, which they readily complied with. This size electrode was the type eventually used in the study.

The long time spent in welding rod selection was gainfully employed in gaining proficiency on the apparatus and in the optimization of welding parameters. Once a suitable rod was found, the experience gained in welding at high pressures allowed rapid selection of optimum welding parameters.

4.6.1 Initial Attempts

Initial attempts to conduct high pressure welds were accomplished using the LB-52UL rods suppplied by Kobe Steel. Problems encountered included arc initiation, sustaining the

AD-A190 255 CRACKING TENDANCIES OF RESTRAINED WELDS IN HIGH 2/2
STRENGTH LOW ALLOY STEELS (U) MASSACHUSETTS INST OF
TECH CAMBRIDGE DEPT OF OCEAN ENGINEERIN R NI JUN 87
UNCLASSIFIED N00228-85-G-3262 F/G 11/6.1 NL



MICROCOPY RESOLUTION TEST CHART

arc, and irregular weld bead profile. Significant amounts of time were spent in establishing the optimum electrode tip relationship with respect to the sample and welding parameters to achieve the most satisfactory weld possible. However, the problem of minimizing the weld bead irregularities continued to plague these efforts. Significant amounts of time were spent in varying and rechecking voltage, amperage, arc travel speed, and sensitivity in attempts to reduce weld bead irregularities.

4.6.2 Description of Weld Bead Irregularities

Significant weld bead irregularities resulted from using all welding rods at high pressure with the exception of the Hobart 7018 electrodes. The resultant weld bead surface profile would have very inconsistent and erratic weld deposition patterns, and numerous ridges, giving the appearance of a 'cold weld'. The weld deposition rate was very irregular. Even though the workpiece was passing underneath the welding rod at constant speed, the weld deposition rate would cyclically raise and lower, resulting in areas of the weld bead where weld metal deposits were much greater than in other areas, aand areas where the weld deposit was very sparse. The effect of having a very erratic welding arc at high pressures was also reflected in the fact that the point of maximum deposition rate was not always in the center of the weld bead. The result was a very irregular shaped weld bead, as if the welding was done manually by a person who had an unsteady hand resulting in inconsistent welding speed and a wavering from side to side. The cyclic nature of the raising and lowering of the weld deposition rate or the wandering of the maximum weld deposition rate from side to side was very erratic and of no discernable period.

4.6.3 Welding Rod Search

Consultations with Kobe Steel revealed that Kobe Steel was not constraining the research to using the LB-52UL electrode that they had provided. Indeed, this particular type electrode had had no hyperbaric welding experience. The literature on the subject notes that the welding consumable plays an important part in obtaining satisfactory welds at high pressure. Many of the private contractors who conduct hyperbaric underwater welding are reported to utilize their own proprietary consumables. While it was highly unlikely that I would be able to gain access to these proprietary consumables, I endeavored to gain more information on the mechanics of conducting underwater welds and to determine exactly which "off the shelf" electrodes, if any were being used in the field.

In conversations with several consultants in the field of underwater welding, I was able to learn that:

(1) Higher amperages were required to conduct welding at high pressures. This was consistent with my experience of having to use amperages higher than the manufacturer's

recomendations. One consultant did relate to me that his company had found no change of welding parameters was necessary down to 132 ft (59 psig). While my experience did not verify this fact, it did not counter it because the pressures I was dealing with were much higher.

(2) Welding consumables do play an important part in obtaining satisfactory hyperbaric underwater welds, but it was not uncommon to use off the shelf electrodes in performing hyperbaric underwater welds. Welder expertise and

irregularities that might show up in a constant travel situation. I was provided with the types of welding rods that they had had positive experiences with (Chemtron and Atomic Arc 7018).

The importance of having the proper consumable is also evidenced by another example. Some of the trial runs at pressure were conducted with an Easy-Arc 7014 electrode. While no problems with arc-initiation occurred, as expected due to the 7014's iron content in the coating, the resultant weld bead exhibited severe porosity. This porosity can be attributed to the insufficient amount of protective vapor generated from the welding rod coating during welding at high pressures.

The following rods were obtained and tested to determine the welding rod which would exhibit the best high pressure welding characteristics.

electrode type	diameter (mm)
LB-52UL	3.2
LB-52UL	4.0
LBM-52	3.2
LB-52UL	3.2 (0.2 mm smaller diameter flux coating)
LB-52UL	3.2 (0.4 mm smaller diameter flux coating)
Atomic Arc 7018	3.2
Airco 7018	3.2
Lincoln 7018	3.2
Hobart 7018	3.2

All rods except the Hobart rod exhibited varying degrees of weld bead surface irregularities when welded at high pressure. The Atomic Arc and Airco rods had somewhat better characteristics than the other rods. The Hobart 7018 rod's weld bead profile, when welded at high pressure, in marked contrast to the above, was exemplary in all respects. It was uniformly deposited and had a surface and crossectional profile that could not readily be distinguished from the weld bead profile of a weld conducted at 0 psig.

4.6.4 Observations on Welding and Arc Stability

The literature and conversations with welding consultants indicated that because of increasing arc instability at high pressures, both a smaller diameter welding rod, and a shorter arc lengths were required to obtain satisfactory welds. These observations were found to be true during the conduct of this thesis.

Observations of arc stability and resultant weld bead profiles indicated that arc stability was a function of consumable, arc length, amperage, and electrode diameter. Arc stability could be enhanced by: (1) decreasing the diameter of the weld rod, (2) increasing the amperage, (3) decreasing the arc length.

Excessive arc instability caused voltage fluctuations that could cause the arc to extinguish either through the ALC sensing a burn through condition or from other considerations. On numerous occasions under hyperbaric conditions, the arc would just go out. The reason is unclear, but could possibly be attributed to excessive arc instability. Of course, once the arc went out, a glob of flux would form over the electrode tip and prevent a subsequent arc initiation.

Another phenomena that was observed was that at high pressures with the LB-52UL rod, almost globular transfer seemed to occur, whereas at 0 psig spray transfer occurred.

Probably the most perplexing phenomena that occurred during high pressure welds was that the rod seemed to stick in the weld pool. Motion of the constant speed cart and workpiece under the stationary electrode was easily distinguishable. On some occasions, the rod seemed to stick in the weld pool, as observed by the supposedly stationary electrode and arc moving slightly. The welding rod and arc would be observed to jump or spring back to the original position when the cart had moved the workpiece a sufficient distance for the bending weld rod to generate enough spring force to overcome whatever was causing the arc and welding rod to stick to the workpiece. On the occasions when this did occur, I raised the set voltage, which increased the welding arc length. This appeared to solve the problem.

It is interesting to note that the welding rod recommended to me by a consultant in underwater welding practices was not the ultimate welding rod selected by me in this thesis. While the welding rods recommended by him (Atomic Arc or Chemtron E7018) had superior weld bead profiles and cross sectional characteristics than the previous rods tested, they still exhibited significant surface irregularities and inconsistent weld deposition rates. The weld bead characterisics of the Hobart E7018 rod were vastly suuperior to any of the other rods tested and had weld bead characteristics at high pressure almost exactly similar to a 0 psig weld.

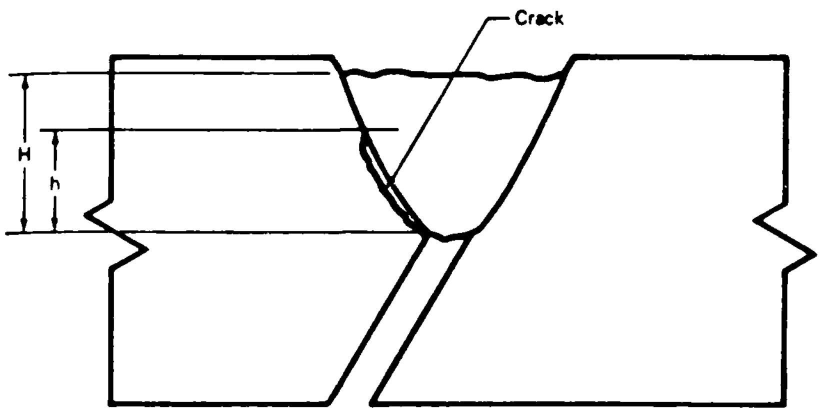
This may be indicative of the fact that while for the purposes of this thesis, the Hobart E7018 rod was vastly superior, in the field, with the aid af a skilled welder, the other rods tested might serve equally as well. The price you would pay in the field by using the other welding rods would be that the welder would have to be a better welder and be more attentive to controlling his rod travel to compensate for the irregularities exhibited by the other rods. A key difference in the manner in which this thesis' apparatus was set up is that I was not able to introduce the manual dexterity of a welder in obtaining satisfactory welds.

4.7 Methodology Summary

As a result of the above observations, it was decided to utilize the 3.2 mm Hobart E7018 electrode at a very high amperage (190 amps) when welding at high pressures. Welding was conducted at three pressures: 0 psig, 100 psig (68.5m depth) and 200 psig (137m depth). 100% re;ative humidities were used at all pressures for comparisons. At 0 psig, welding would also be conducted at the welding laboratory ambient humidity. A "wet" condition would be also evaluated to see how extreme moisture conditions would effect weld cracking. No preheat would be used in any welding. Normal atmosphere would be used for pressurization.

4.8 Data and Results

This section will provide the testing parameters and results from the conduct of this research on hyperbaric welding. Table 4-1 provides the environmental and welding parameters used. Table 4-2 provides the results of the Lehigh cracking tests. Where cracking occurred, the degree of cracking is indicated by using the cracking ratio, which is the ratio of the crack length as compared to the weld depth. (see Figure 4-1) The Lehigh test is most useful in evaluating electrodes because cracking occurs in the weld metal. The cracking in these Lehigh tests occurred predominately in the weld metal, but also occurred in the HAZ, to varying degrees in the different metals. This indicates that the base metals are evaluated with the Lehigh test.



Cracking ratio

$$= \frac{\Sigma h}{\Sigma H} \times 100$$

Figure 4-1 Determination of a Cracking Ratio
(Reference 12)

Using the analytical/empirical system for preventing cold cracking in steel weldments presented in Section 14.33 of Reference 1, calculation of cracking sensitivity, critical cooling times and preheat required were conducted for the steels and pressures. Preheat requirements are tabulated in Table 4-2. These results indicate that preheat should have been applied to the Type II steel to prevent cracking. This was not done, yet no cracking occurred. This substantiates that the system presented to prevent cracking may not be totally applicable to the low carbon equivalent steels, such as the Type II and III steels used in this thesis. This conjecture has been presented earlier by Reference 5.

The test results generally substantiate that the lower the cracking sensitivity, the more resistant the steel is to hydrogen cold cracking. The Type I steel, which had the highest carbon equivalent values and cracking sensitivity values, had cracking under all pressures and humidity conditions except for the dry atmosphere at 0 psig.

The Type II steel did not sustain any cracking at any pressures at 100% humidity. The Type III steel (with the lowest cracking sensitivity) only had one crack over the test range pressures at 100% humidity. This occurred at 200 psig . A check sample, welded at 200 psig and 100% humidity, however did not sustain any cracking.

Both Type II and Type III samples, welded under "wet" conditions at 100 psig, sustained cracking. This might be expected due to the much larger amount of hydrogen due to the very wet environment.

TABLE 4-1

TESTING PARAMETERS

Type I Steel

T_{wet} (C)	T_{dry} (C)	Relative Humidity (%)	Psig	Volt	Amps
26	16	34	0	22.4	150
25	26	92	0	23.2	155
27	27	100	100	21.6	190

(note: Wet weld at 100psig not done - assumed to crack)

26	26	100	200	22.4	280

Type II Steel

T_{wet} (C)	T_{dry} (C)	Relative Humidity (%)	Psig	Volt	Amps
26	16	34	0	22.4	150
25	26	92	0	23.2	155
27	27	100	100	21.6	190
27	27	Wet*	100	21.6	190
26	26	100	200	22.2	190

TABLE 4-1 (cont)

TESTING PARAMETERS

Type III Steel

T_{wet} (C)	T_{dry} (C)	Relative Humidity (%)	Psig	Volt	Amps
26	16	34	0	22.4	150
25	26	92	0	23.2	155
27	27	100	100	22.2	190
27	27	Wet*	100	21.6	190
26	26	100	200	22.2	190
26	26	100	200	22.4	190

NOTE: For all runs:

Welding electrode:	1/8 in. (3.2mm) Hobart E7018
Touch retract:	2
Start adjust:	10
Cart travel:	7 in/min
Sensitivity:	1
HF start:	ON

Table 4-2

LEHIGH CRACKING RESULTS

Tested Steel: Type I (PCM = 0.228, C.E. = 0.373)

Calc Pre-heat (C)	Crack-ing Expect.	Pres-sure (psig)	Humid-ity (%)	Sectioning Locations Start	Middle	End
NR	N	0	34	N.C.	N.C.	N.C.
50	Y	0	92	CR = 100% Complete break		
122	Y	100	100	CR = 20% loc = HAZ	CR = 20% loc = HAZ	N.C.
138	Y	200	100	CR = 100% Complete break		

Tested Steel: Type II (PCM = 0.193, C.E. = 0.315)

Calc Pre-heat (C)	Crack-ing Expect.	Pres-sure (psig)	Humid-ity (%)	Sectioning Locations Start	Middle	End
NR	N	0	34	N.C.	N.C.	N.C.
NR	N	0	92	N.C.	N.C.	N.C.
44	Y	100	100	N.C.	N.C.	N.C.
--	--	100	WET	CR=100%	CR=100%	CR=100%
81	Y	200	100	N.C.	N.C.	N.C.

Tested Steel: Type III (PCM = 0.154, C.E. = 0.292)

Calc Pre-heat	Crack-ing Expect.	Pres-sure (psig)	Humid-ity (%)	Sectioning Locations Start	Middle	End
NR	N	0	34	N.C.	N.C.	N.C.
NR	N	0	92	N.C.	N.C.	N.C.
NR	N	100	100	N.C.	N.C.	N.C.
--	--	100	WET	CR=15%	CR=50%	CR=100%
NR	N	200	100	N.C.	N.C.	CR=25%
NR	N	200	100	N.C.	N.C.	N.C.

NR = Not Required
N.C. = No cracking detected
CR = Cracking Ratio

V. CONCLUSIONS

1. Emulation of the underwater conditions experienced in underwater hyperbaric welding using the SMA welding technique was effectively conducted using the welding and simulation apparatus described in this thesis. Deviations from actual welding conditions involved those aspects of the welding sequence which could not use the facilities and capabilities of an intelligent and skilled welder, i.e., the manual dexterity of the welder, and the facility of the welder to execute procedures to minimize the welding electrode from excessive exposure to the humid environment. The normal inert gas Heliox environment was also not utilized, for economical reasons, however this capability certainly can be incorporated into the apparatus.

2. Welding under hyperbaric conditions will have an adverse effect on the hydrogen cracking of high strength steels due to a combination of the following major effects:

A. As pressure increases, for the same relative humidity, the water content of the atmosphere becomes greater, thus providing a larger source of hydrogen to enter the weld pool and be absorbed into the welding electrode.

B. As pressure increases, when welding in a compressed normal atmosphere composition, the partial pressure of hydrogen increases, thus providing an increased source of hydrogen to enter the weld pool.

C. As pressure increases the solubility of hydrogen into the weld pool increases.

D. For purposes of hydrogen cracking control, it would be desirable to use a high heat input process. However, the adverse effect of pressure increases on welding arc characteristics, and the resultant effect on the welding parameters necessary to achieve satisfactory welding conditions, results in a relatively low heat input process due to the small electrodes used.

3. Consistent with the theories pertaining to the determination of cracking susceptibility P_w and the prevention of hydrogen cold cracking: as the quality of HSLA steel increases, i.e., as PCM or C.E. lowers for a constant yield strength, the steel's resistance to hydrogen cold cracking improves. Use of low Pcm steels in underwater structures will facilitate repairs conducted under hyperbaric conditions due to their decreased susceptibility to hydrogen cold cracking. It is significaant to note that for the adverse welding conditions existing in the tank, i.e. no humidity or electrode control, no preheat or post heat, etc., that no preheat was required for the Type III HSLA by analytical calculation, and that essentially no cracking was experienced for the HSLA steels subjected to 100% humidity.

Cracking was experienced when subjected to direct moisture, i.e. "wet" conditions.

4. It is apparent that hyperbaric welding conditions are inherently detrimental to the prevention of hydrogen cold cracking. Welding environmental conditions should be controlled to minimize the possibility of hydrogen entering the weldment, including the maximum use of inert gas shielded welding methods. Selection of steels with low PCM or C.E. should also be encouraged to maximize the chances of not inducing hydrogen cold cracking. HSLA steels satisfy the requirement of low PCM (C.E.) with high yield strengths, and should be favored over high PCM (C.E.) steels for use in underwater platforms.

5. This study substantiates that the current methods for preventing cold cracking in steel weldments may not be entirely applicable to low Pcm HSLA steels. As presented in Reference D, current carbon equivalent formulas have underated a low Pcm (Ceq) steels susceptibility to cold cracking (i.e., indicates that preheat is required, when in actuality, preheat is not required to prevent cracking).

VI. RECOMENDATIONS

1. To fully employ the cracking susceptibility and cracking prevention theories presented in the literature, it is necessary to be able to predict the resultant hydrogen content of the weld metal. Under hyperbaric conditions, this becoomes a difficult task, because it is a function of so many variables, e.g., pressure, weld process used, initial moisture content of electrode, ambient humidity, exposure time of electrode to humidity, arc length, purge gas utilized, etc. Modeling of some of these variables has already been accomplished. It would be very beneficial to model more completely the pressure dependent variables encountered under hyperbaric welding conditions in an analytical model that could predict hydrogen content of the weld metal. Once this has been accomplished, comparison of hydrogen weld cracking susceptibility can be accomplished, comparing the weld cracking suscrptibility of similar materials with the same hydrogen weld content, welded under different pressures. Differences in cracking susceptibility would indicate other pressure dependent variables that affect the hydrogen weld cracking susceptibility of materials.

2. In view of the difficult time experienced in obtaining a suitable consumable to conduct this thesis, it is recommended that studies be conducted to see what effect different materials and material combinations in the consumables have

on the welding arc and resultant weld bead characteristics at pressure. This would facilitate further research on hyperbaric welding using consumables.

3. Further research needs to be conducted on determining applicable equations for carbon equivalents and/or cracking susceptibility that can accurately determine a low carbon equivalent HSLA steel's need for preheat, postheat, and cooling off times.

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